THE ELEMENTS

OF

ELECTRICAL TRANSMISSION

A TEXT-BOOK FOR COLLEGES AND TECHNICAL SCHOOLS

BY

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PREFACE.

In preparing the material for this book, it has been the author's aim to present those things which should be grouped and articulated in order to afford an elemental study of the broad subject of the generation, transmission, distribution and utilization of power by electrical processes. The title of the work only partially covers this field, but was chosen with a view to brevity and convenience. In fact, our language needs some modest word for so large a subject.

Necessarily, the material available far exceeds the capacity of any single volume, but the attempt is made to provide a working text-book which may serve as a more or less complete course, depending upon the amount of time available for the subject. It is hoped that it may serve as an outline for even an extended course, supplemented always by that most important source, the teacher. Nevertheless, the book will probably stand or fall as an elementary text-book, which is all that it desires to be.

It is proper to discuss subjects which have been presented in other books, because they are important features. It has also seemed wise to provide certain discussions not elsewhere available because, sooner or later, the student feels the need of them. Under this head would come the matters of self-induction and capacity of polyphase circuits as derived from single-phase circuits, line calculations, standing waves, traveling waves, curve calculations, etc. Further comment might be made upon each of these topics and it seems necessary to speak particularly of the methods presented in making line calculations. Here, there are given several processes, each used more or less commonly. They are all presented in detail in order that contrasts may be made and the simplicity of the series approximation emphasized.

As is pointed out, the matter of corona is not analyzed minutely. It, rather, has been simplified as much as is consistent with the fundamental conceptions of the phenomenon.

In the chapter upon distribution, the attempt is made to summarize in clear statements the chief characteristics of various units which go to make up the load upon an electrical system and will determine for it its distinctive features.

The author desires to acknowledge his indebtedness to many friends and manufacturing companies for material and counsel, the free use of which has influenced every page of his manuscript. Of no one may this be more truly said than of Dr. Charles P. Steinmetz, the author's obligation to whom cannot be measured.

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CHAPTER I.

CONDUCTORS AND INSULATION.

Measurement of Conductors.—There are several different methods of indicating the size of a conductor employed in the electric transmission of energy. These methods vary with locality and with the natures of the conductor employed. We are confronted by different gages where identical numbers correspond to different diameters of circular wire. A conductor may be rated by the diameter, or by the area of the cross-section, which is perhaps the most satisfactory method when considering its conductivity independently of the shape and dimensions.

Here, again, the area may be expressed in square inches, square mils or circular mils, where the English system of measurements is used. A conductor not circular in cross-section is sometimes defined by the number of the equivalent circular wire, as for example, the figure-eight trolley wire may be called a No. 0000, etc.

A unit called the mil is introduced in order to avoid fractional numbers for diameters. The mil is one one-thousandth of an inch. It is used with either circular or rectangular conductors.

In stating the area of a wire it may be done in terms of *square mils* or *circular mils*. The latter term has the unit of area equal to a circle of one mil diameter. Hence a round wire 0.5 inch in diameter is a 500-mil wire. Its area in square measure is 0.1965 square inch or 196,500 square mils. It is, however, equal to 500^2 circles of one mil diameter, hence, 250,000 circular mils.

The introduction of this unit avoids the use of the factor $\pi/4$ in determining the area, and where relative values are desired, it is all that is necessary.

The use of gages becomes more and more unsatisfactory from year to year and there seems to be some little tendency toward a greater usage of diameter or area as the descriptive term of

identification. When wire gages were first constructed the numbers assumed were used to cover the range of sizes then in demand. But here, as elsewhere, demands have changed, and larger wires have no orderly place in the series, as is evidenced by the presence of such terms as No. 000, No. 0000, etc. The usage is, however, universal, and if not best practice, it is at least good standard practice and will be met with upon every turn.

In America, the B. & S. (Brown and Sharp) Gage is the most common one. The Imperial Standard Wire Gage is most used in England while Birmingham or Stubbs Wire Gage is also used. The B. & S. Gage is frequently known as the American Wire Gage. Table I gives the diameters of wires of these different gages.

Table I.—Comparison of Wire Gages.

Gage number.	B. & S. G. A. & W. G.	I. S. W. G.	B. W. G. S. W. G.
0000	460.0	400	454
000	410.0	372	425
00	365.0	348	380
0	325.0	324	340
1	289.3	300	300
2	258.0	276	284
3	229.4	252	259
4	204.3	232	238
5	182.0	212	220
6	162.0	192	203
7	144.2	176	180
8	128.5	160	165
9	114.4	144	148
10	102.0	128	134
11	91.0	116	120
12	81.0	104	109
13	72.0	92	95
14	64.1	80	83
15	57.1	72	72
16	51.0	64	65
17	45.3	56	58
18	40.3	48	49
19	36.0	40	42
20	32.0	36	35

It is a noteworthy feature of the B. & S. gage that an increase of three in the gage number divides the area of the wire by two. That is, No. 5 wire is twice the area of cross-section No. 8 wire. Successive numbers differ in area by the factor $\sqrt[3]{2}$ or 1.2599. No. 4 wire will, therefore, be 1.26 times as large in cross-section as is No. 5.

For rough calculations we may deduce the approximate properties for copper wires by remembering that No. 10 wire by B. & S. gage is about 0.1 inch in diameter and has a resistance of one ohm per 1000 feet, and weighs 32 pounds per 1000 feet. For example, to estimate data upon No. 8 wire:

Approximate area of No. 8 will be 1.26^2 times area of No. 10. Or $1.26^2 \times 10{,}000 = 15{,}900$ C. M.

Diameter No. 8 = 1.26 times diameter No. 10 = 0.126 in.

Resistance No. $8 = 1/(1.26)^2$ times resistance No. $10 = 0.63$ ohms per 1000 feet.

Weight of No. 8 per 1000 feet $= 1.26^2\,(32)$ pounds $= 50.8$ pounds.

Comparing these values with tables we have for No. 8 wire

	Actual.	Approximate.
Area	16,384	15,900 C. M.
Diameter	128	126 mils.
Resistance per 1000 ft	0.6214	0.63
Wt. per 1000 ft.	50	50.8 lbs.

Or, it will be seen from the above that a change of ten sizes gives the factor 10 in comparing areas of cross-section, for we have the continued multipliers, $2 \times 2 \times 2 \times 1.26$. An increase in size number by 10, therefore, gives one-tenth the area of cross-section and ten times the resistance. By combinations of these two changes, by threes or by tens, any gage number may be reached from any other one. This is sufficiently accurate for ordinary preliminary calculations or estimates.

In the Edison or Circular Mil Gage, the gage number is identical with the number of thousands of circular mils of area of the wire. For example, No. 5 wire will be of area 5000 circular mils, No. 80 of 80,000 circular mils, etc. Hence, the gage number multiplied by 1000 gives the circular mil area; or the gage number multiplied by 250π gives the square mil area.

The current-carrying capacity of a wire does not vary as the

area of cross-section, because the radiating surface does not increase in the same proportion. If

w = watts radiated per unit area conductor surface,
r = resistance of conductor,
s = surface of conductor,
d = diameter of conductor,

we have, for constant temperature

$$s \propto d$$

$$w \propto i^2 r$$

$$r \propto \frac{1}{d^2}$$

$$\therefore w \propto \frac{i^2}{d^2}$$

$$\frac{w}{s} \propto \frac{i^2}{d^3} = \text{constant.}$$

$$\therefore i \propto d^{\frac{3}{2}}$$

Copper wire is almost universally manufactured by drawing. We meet with both *hard drawn* and *soft drawn* or *annealed* copper wire. The difference, from the standpoint of manufacture, lies in the fact that the soft drawn wire is annealed more frequently in the process of drawing than is the hard drawn. This gives a softer and weaker strand of better conductivity than is acquired by hard drawing. The difference in conductivity favors the soft drawn wire by 3 per cent. or 4 per cent., while the tensile strengths show a decided superiority of the hard wire. In fact, they may vary as much as from 35,000 pounds per square inch for soft wire to 65,000 pounds per square inch for hard wire.

Roeblings give as comparative values the figures shown in Table II.

Table II.—Tensile Strength of Copper Wire.

Numbers B. & S. G.	Breaking weights—pounds.	
	Hard drawn.	Annealed.
0000	8,310	5,650
000	6,580	4,480
00	5,226	3,553
0	4,558	2,818
1	3,746	2,234
2	3,127	1,772
3	2,480	1,405
4	1,967	1,114
5	1,559	883
6	1,237	700
7	980	555
8	778	440
9	617	349
10	489	277
11	388	219
12	307	174
13	244	138
14	193	109
15	153	87
16	133	69
17	97	55
18	77	43
19	61	34
20	48	27

Matthiessen's figures as recommended by a committee appointed by the A. I. E. E. are used as a basis for resistance values given in these pages.

One mil-foot of soft copper has resistance of 9.38 international ohms at 0° C.

One mil-foot of hard copper has resistance of 9.59 international ohms at 0° C.

If we have a soft copper wire 0.5 inch diameter, its resistance per thousand feet will be

$$R=\frac{9.38\times 1000}{500^2}=0.03752 \text{ ohms.}$$

For hard drawn wire it will be per thousand feet

$$R=\frac{9.59\times 1000}{500^2}=0.03836 \text{ ohms.}$$

The resistance of a 100-foot copper strip 300 mils by 60 mils will be

$$R=\frac{9.38\times 100}{\dfrac{60\times 300}{\pi/4}}=0.0409 \text{ ohms.}$$

In this calculation the area of the rectangular cross-section may be expressed in the terms of *circular mils* (C. M.). This is done by the reduction factor $\pi/4$, for

Area in square mils $=\pi/4$ (area in circular mils).

Formulæ expressing these facts will be, if L = number of feet length,

$$R \quad \text{(hard copper)} =\frac{9.59L}{C.M.}=\frac{7.53L}{\text{sq. mils.}} \text{ ohms at } 0^\circ \text{ C.}$$

$$R \quad \text{(soft copper)} =\frac{9.38L}{C.M.}=\frac{7.37L}{\text{sq. mils.}} \text{ ohms at } 0^\circ \text{ C.}$$

Table III gives data upon copper wire measured according to the B. & S. gage. Table IV similarly gives the data where the diameter of wire is expressed in mils.

If a comparison is desired between these units of measure and the metric system, we may obtain metric measures of any wire by multiplying its diameter in mils by the reduction constant 0.0254001, giving diameter in millimeters. That is, a circular wire of 3/8 inch diameter (375 mils) is $375\times 0.0254001=9.525$ mm. $=0.9525$ cm. in diameter.

No. B. & S. G.	Diameter in mils.	Area in Square mils.	Area in Circular mils.	Weight in lb. per 1000 feet.	Weight in lb. per Mile.	Resistance in ohms as 20° C. per 1000 feet.	Resistance in ohms as 20° C. per Mile.	Diameter in mm.	Carrying capacity amp. 16° F. rise, concealed.	Carrying capacity amp. 32° F. rise, open.
0000	460.0	166,200	211,600	640.5	3,381	0.04893	0.2583	11.683	210	312
000	409.6	131,800	167,805	508.0	2,682	0.06170	0.3258	10.404	177	262
00	364.8	104,500	133,079	402.8	2,127	0.07780	0.4108	9.266	150	220
0	324.9	82,900	105,534	319.5	1,687	0.09811	0.5180	8.251	127	185
1	289.3	65,700	83,694	253.3	1,337	0.12370	0.6531	7.348	107	156
2	257.6	52,100	66,373	200.9	1,062	0.1560	0.8237	6.544	90	131
3	229.4	41,300	52,633	159.3	841.1	0.1967	1.0386	5.827	76	110
4	204.3	32,800	41,742	126.4	667.4	0.2480	1.3094	5.190	65	92
5	181.9	26,000	33,102	100.2	529.0	0.3128	1.6516	4.621	54	77
6	162.0	20,600	26,250	79.46	419.5	0.3944	2.0824	4.115	46	65
7	144.3	16,400	20,817	63.02	332.7	0.4973	2.6257	3.665	39	55
8	128.5	13,000	16,509	49.98	263.9	0.6271	3.3111	3.263	33	46
9	114.4	10,300	13,094	39.63	209.2	0.7908	4.1754	2.906	28	38
10	101.9	8,150	10,381	31.43	166.0	0.9972	5.2652	2.588	24	32
11	90.74	6,460	8,234	24.93	131.6	1.257	6.6370	2.305	20	27
12	80.81	5,130	6,530	19.77	104.4	1.586	8.374	2.052	17	23
13	71.96	4,070	5,178	15.68	82.79	1.999	10.560	1.828	14	19
14	64.08	3,230	4,107	12.43	65.63	2.521	13.311	1.628	12	16
15	57.07	2,560	3,257	9.858	52.05	3.179	16.785	1.449	9	12
16	50.82	2,030	2,583	7.818	41.28	4.009	21.168	1.291	6	8
17	45.26	1,610	2,048	6.200	32.74	5.055	26.690	1.150	4.5	6.5
18	40.30	1,280	1,624	4.917	25.96	6.374	33.655	1.024	3	5
19	35.89	1,010	1,288	3.899	20.59	8.038	42.440	0.9116	2.3	4
20	31.96	800	1,022	3.092	16.33	10.14	53.540	0.8118	1.5	3

Table IV.—Data on Copper Wire, Mil Measurement.

Diameter in mils.	Area of cross section. Circular mils.	Area of cross section. Square mils.	Pounds per 1000 feet.	Resistance per 1000 feet.
460	211600	166200	640.5	0.04893
410	168100	132100	510.0	0.06143
365	133200	104700	403.5	0.0777
325	105600	83000	320.0	0.0979
289	83520	65700	253.4	0.1236
258	66560	52300	201.9	0.1552
229	52440	41200	159.0	0.1970
220	48400	38010	146.8	0.2135
204	41620	32690	126.2	0.249
193	37250	29260	112.9	0.278
182	33120	26010	100.3	0.312
172	29580	23230	89.6	0.353
162	26240	20620	79.6	0.394
153	23410	18400	71.0	0.4415
144	20740	16300	62.8	0.499
134	17960	14110	54.4	0.576
129	16640	13080	50.5	0.620
120	14400	11310	43.6	0.718
114	13000	10210	39.4	0.795
109	11880	9340	36.0	0.871
102	10400	8180	31.5	0.995
95	9025	7095	27.37	1.145
91	8281	6505	25.1	1.249
86	7396	5810	22.4	1.399
81	6561	5160	19.9	1.573
76	5776	4540	17.5	1.79
72	5184	4075	15.71	1.992
68	4624	3635	14.01	2.235
64	4096	3220	12.4	2.525
61	3721	2920	11.29	2.778
57	3249	2550	9.85	3.18
54	2916	2290	8.84	3.542
51	2601	2045	7.89	3.97
49	2501	1965	7.58	4.135
45	2025	1590	6.14	5.10
42	1764	1387	5.35	5.85
40	1600	1258	4.85	6.465
38	1444	1135	4.38	7.155
35	1225	963	3.71	8.446
32	1024	805	3.11	10.07

Table V.—Resistances of Copper Alloys.

Substances alloyed with pure copper.	Conductivity of hard drawn alloy, pure soft copper being 100.	Temperature centigrade.
Carbon:		Degrees
Copper, with 0.05 per cent. of carbon....	77.87	18.3
Sulphur:		
Copper, with 0.18 per cent. of sulphur....	92.08	19.4
Phosphorus:		
Copper, with 0.13 per cent. of phosphorus	70.34	20.0
Copper, with 0.95 per cent. of phosphorus	24.16	22.1
Copper, with 2.5 per cent. of phosphorus.	7.52	17.5
Arsenic:		
Copper, with traces of arsenic...........	60.08	19.7
Copper, with 2.8 per cent. of arsenic.....	13.66	19.3
Copper, with 5.4 per cent. of arsenic.....	6.42	16.8
Zinc:		
Copper, with traces of zinc..............	88.41	19.0
Copper, with 1.6 per cent. of zinc........	79.37	16.8
Copper, with 3.2 per cent. of zinc........	59.23	10.3
Iron:		
Copper, with 0.48 per cent. of iron......	35.92	11.2
Copper, with 1.06 per cent. of iron......	28.01	13.1
Tin:		
Copper, with 1.33 per cent. of tin.......	50.44	16.8
Copper, with 2.52 per cent. of tin.......	33.93	17.1
Copper, with 4.9 per cent. of tin.........	20.24	14.4
Silver:		
Copper, with 1.22 per cent. of silver.....	90.34	20.7
Copper, with 2.45 per cent. of silver.....	82.52	19.7
Gold:		
Copper, with 3.5 per cent. of gold.......	67.94	18.1
Aluminium:		
Copper, with 0.10 per cent. of aluminium.	12.68	14.0

Table VI.—Hard Drawn Copper Telephone Wire Specifications. (British Post-office).

Diameters			Weights per mile.			Minimum breaking strain in pounds.	Minimum number of twists.	Maximum resist. per mile at 60° F. internat'l ohms.
Required.	Maximum.	Minimum.	Required.	Maximum.	Minimum.			
224	226	220.5	800	820	780	2400	In six in. 15	1.098
194	196	191.0	600	615	585	1800	20	1.464
158	160.25	155.5	400	410	390	1300	25	2.195
112	113.25	110.5	200	205	195	650	In three in. 20	4.391
97	98	95.5	160	153.75	146.25	490	25	5.855
79	80	78.0	100	102.5	97.5	330	30	8.782

Table VII.—Hard Drawn Copper Telephone Wire Specifications.

Numbers.		8 B. W. G.	12 N. B. S. G.	10 B. & S. G.	12 B. & S. G.	14 B. & S. G.
Diameters in mils	Required	165.0	104.0	101.9	80.0	64.0
	Maximum	166.0	104.9	102.8	81.2	65.0
	Minimum	164.0	103.1	101.0	79.3	63.0
Weights per mile	Required	436.4	173.4	165.0	102.6	65.0
	Maximum	441.7	176.4	168.0	105.7	67.5
	Minimum	431.1	170.4	162.0	100.8	63.0
Breaking weights	Actual required	1328	549	540	334	220
	Actual minimum	1301	538	519	327	212
	Per square inch	62100	64600	64800	66500	68200
Weights of coils	Maximum	218	219	218	72	
	Minimum	152	151	152	52	
Conductivity	Required	97	97	97	97	97
	Minimum	96	96	96	96	96
Twists in six inches		30	40	40	44	47
Per cent. elongation in five feet		1.14	1	0.99	0.94	0.91

Specifications usually state that a copper wire must have a conductivity of not less than 98 per cent. of that of pure copper. That the conductivity varies widely with changes in composition is shown by Table V.

Hard drawn copper is used for telephone lines. In Great Britain, where there is government control of telephone service, the Post Office specifications for copper wire are carefully outlined. Including Tables VI and VII, they are in part as follows:

"The wire shall be capable of being wrapped in six turns around wire of its own diameter, unwrapped and again wrapped in six turns around wire of its own diameter in the same direction as the first wrapping without breaking; and shall be also capable of bearing the number of twists set down in the table, without breaking.

"The twist-test will be made as follows: The wire will be gripped by two vises, one of which will be made to revolve at a speed not exceeding one revolution per second. The twists thus given to the wire will be reckoned by means of an ink mark which forms a spiral on the wire during torsion, the full number of twists to be visible between the vises."

According to the above table, the *mile-ohm* of copper required is 878 pounds. This corresponds to a conductivity of 97.8 per cent., taking the value of the mile-ohm of 100 per cent. copper as 859.

As here seen, a different unit is used in consideration of conductors for the use of telephone or telegraph, called the *mile-ohm* of wire. It is the weight of a certain material which will have 1 ohm resistance per mile length. It is, in a sense, a combined measure of conductivity, diameter, weight, etc.

Aluminium.—The use of aluminium for electric conductors is very frequent. Where economy of space is necessary it would never be used in place of copper, as for instance, in armature windings, transformer coils, etc., etc. However, wherever this space economy is not demanded, we may consider the use of aluminium.

It is much lighter than copper. It has a lower conductivity than copper. Its tensile strength is less than that for copper. Put into figures the comparison may be stated thus:

Specific gravity.		Conductivity.	Tensile strength.	Elastic limit.
Copper	8.93	96 to 99	30000 to 68000	20000
Aluminium	2.68	61 to 63	20000 to 35000	15000

Assuming average conductivities of 97 and 62 respectively, we find for equal conductivities, copper and aluminium wires must bear the ratio of cross-section,

$$\text{Copper to aluminium } = \frac{1}{97} : \frac{1}{62} = 1.0000 : 1.5645.$$

By comparison with wire tables, it is evident that this difference in area corresponds almost exactly to a change of two B. & S. gage numbers. For example, a No. 10 copper wire may be replaced by a No. 8 aluminium wire so far as conductivity is concerned. The latter really gives a slightly increased conductivity by the ratio of 1.26^2 to $1.5645 = 1.015$ or 1.5 per cent. increase.

The weights of equal volumes bear the ratio:

Copper to aluminium $= 8.93 : 2.68 = 1.000 : 0.300$. For any given diameter the weight of aluminium wire is 0.3 of the weight of a copper wire. Or for equal conductivities,

$$\text{Copper to aluminium } = \frac{8.93}{97} : \frac{2.68}{62} = 1.00 : 0.469.$$

The weights of a span of copper wire will be 1/0.469 times the weight of the equivalent aluminium span or 2.13 times as great.

It will be noted that, as for equal conductivities the aluminium conductor has 1.56 times the cross-section of the copper conductor, it presents this much greater body to the pressure of wind and for the formation of ice. In some localities both of these factors are serious considerations.

In order not to exceed the elastic limits of the materials we may assume about 14000 pounds per square inch for aluminium, and 18000 to 25000 pounds per square inch for copper.

It is necessary to keep tensions much below the test values for these materials, owing to the fact that under continued strain the molecules of the metals will gradually flow and the wire will become permanently elongated and diminished in diameters.

Or, using tensile strength as the basis of comparison,

Aluminium	33,000 pounds per square inch.
Copper—hard drawn....	60,000 pounds per square inch.
Copper—soft drawn.....	35,000 pounds per square inch.

By referring to Table VIII, the coefficients of expansion of copper and aluminium are found to bear the ratio of 1 to 1.38. This indicates that aluminium will sag more in hot weather and tighten more in cold weather than does copper.

Table VIII.—Properties of Copper, Aluminium and Iron.

	Copper.	Aluminium	Iron.
Specific gravity............	8.89	2.68	7.7
Weight in lbs. per cu. in.....	0.3215	0.097	0.278
Electrical resistance in ohms per cu. cm. at 0° C........	1.59×10^{-6}	2.46×10^{-6}	900×10^{-6}
Melting point in degrees C..	1100	640	1650
Specific heat at ordinary temperatures. (about)	0.093	0.22	0.11
Coefficient of expansion per degree F.	9.28×10^{-6}	12.8×10^{-6}	6.9×10^{-6}

It is evident from the foregoing figures that aluminium should never be used where the conductor is to be insulated. Taking two wires of equal conductivity we find that their diameters have the ratio, copper to aluminium, of 1 to 1.25. Hence, with insulation of equal depths, it will require nearly 25 per cent. more material for the protection of the aluminium circuit than for that of the copper circuit. The lighter the insulation, the nearer the percentage approaches to 25 per cent. As insulating materials are expensive this item becomes prohibitive for aluminium.

In comparing prices the proper basis is not per pound of

material but upon equality of conductivity. As we have seen, for equal conductivity aluminium is only 46.9 per cent. as heavy as copper. Hence we can pay for aluminium $\frac{1}{0.469}$ (=2.13) times the current price of copper. At present prices of copper, 13.5 cents, aluminium would have a comparative value of 2.13 times 13.5 cents, or 28.7 cents per pound.

As before noted, use of aluminium cannot be made in all situations. It is, however, well fitted for power transmission and distribution. Its saving in weight being about 53 per cent., it is permissible to lessen strain upon towers, poles, insulator pins, etc., or to increase distance between poles without increasing strains. The accomplishment of either of these ends may, in individual cases, be of the utmost importance, as will be shown in the discussion of line construction.

A further consideration, sometimes important, is that with fewer towers or poles there are fewer points of support for leakage currents to ground, or for possible accidental grounds.

Aluminium is frequently installed for heavy feeders for railway or lighting work and for station bus bars. In the former cases, stranded conductors are always used. The bars are flat and thin (comparatively), being so designed that a large amount of surface will be present for radiation of heat. In this respect, aluminium has a decided advantage over copper because large bars are used, hence greater surface presented to air for radiation of heat. For the same i^2r losses dissipated by heat radiation and convection, that conductor will maintain the higher temperature which has the least area of surface. Hence, copper will have higher temperature rises than will aluminium for the same conductivity. This allows the use of less aluminium than the 47 per cent. equivalent copper conductor. Practice indicates that the aluminium bar may be as small as 1.25 times the copper bar. That is, $1.25\times\frac{2.68}{8.93}=0.375$ pounds of aluminium replaces 1 pound of copper. Accepted current densities for aluminium bus bars range between 500 and 1200 depending upon size.

Aluminium is quickly coated by a thin layer of oxid which serves as a protection to the metal. This occurs with the ordinary conditions of moisture in the air. The sulphurous fumes of

locomotive gases do not attack it. Successful joints cannot be made with aluminium by the same methods as for copper. This is due to the fact that no acceptable soldering process has as yet been found. Solder is not necessary from the standpoint of electrical conductivity of a joint. It is added in copper joining as a means of maintaining the perfection of the splice. Incidentally, however, it does increase conductivity, but this is not its prime utility. Similarly, in aluminium, some step must be taken to insure permanence of the joint. This may be accomplished by a more careful mechanical construction of the joint

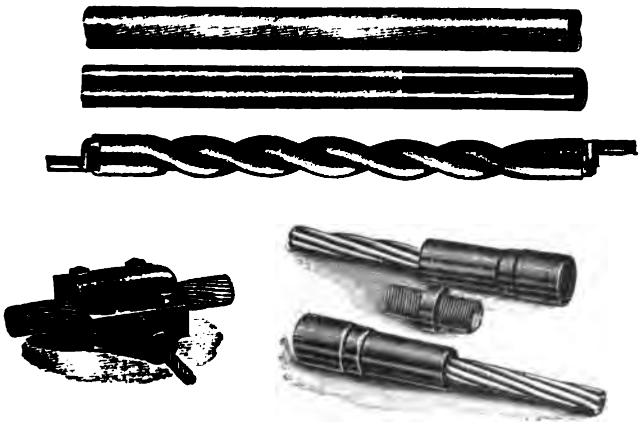


FIG. 1.—Joining aluminium conductors.

by ordinary means. When an aluminium cable is to be spliced it may be opened up farther back than would be done for copper cables and each wire joined by a longer twist to its corresponding wire in the other cable. There are also special means of accomplishing the same end (Fig. 1). A twist joint reinforced by a double sleeve applied before twisting and conforming to the spirals thus made gives a very secure joint. There are also used threaded sleeves compressed upon the ends of the conductors, adjacent sections of the line being joined by use of a stud threaded right hand and left hand. This construction lends itself advantageously to conductors greater than 400 mils diameter. Below this size the twisted sleeve is perhaps best.

Tap-off joints are best accomplished by use of a clamp carrying a side lug for branch connection.

All joining devices, tie-wires, etc., must be of aluminium or there will result local galvanic action. This is generally destructive to the aluminium, because it is electro-positive to a great majority of other metals.

Moreover, the tie-wires should be of annealed wire in order that they may not injure the surface of the conducting strand. Data concerning aluminium wire are shown in Tables IX and X.

Table IX.—Data on Pure Aluminium Wire (Solid).

Conductivity at 62 in the Matthiessen standard scale.

American gage, B. & S. No.	Resistances at 70° F.				Pounds per mile.	Feet per pound.
	Ohms per 1000 feet.	Ohms per mile.	Feet per ohm.	Ohms per pound.		
0000	0.07904	0.41730	12652.	0.00040985	1018.30	5.185
000	0.09966	0.52623	10034.	0.00065102	807.52	6.539
00	0.12569	0.66362	7956.	0.0010364	640.36	8.246
0	0.15849	0.83684	6310.	0.0016479	507.83	10.397
1	0.19982	1.0552	5005.	0.0026194	402.81	13.108
2	0.25200	1.3305	3968.	0.0041656	319.44	16.529
3	0.31778	1.6779	3147.	0.0066250	253.55	20.846
4	0.40067	2.1156	2496.	0.010531	200.90	26.281
5	0.50526	2.6679	1975.	0.016749	159.30	33.146
6	0.63720	3.3687	1569.	0.026628	126.35	41.789
7	0.80350	4.2425	1245.	0.042335	100.21	52.687
8	1.0131	5.3498	987.	0.067318	79.46	66.445
9	1.2773	6.7442	783.	0.10710	62.99	83.822
10	1.6111	8.5065	620.8	0.17028	49.95	105.68
11	2.0312	10.723	492.4	0.27061	39.63	133.24
12	2.5615	13.525	390.5	0.43040	31.43	168.01
13	3.2300	17.055	309.6	0.68437	24.92	211.86
14	4.0724	21.502	245.6	1.0877	19.76	267.17
15	5.1354	27.114	194.8	1.7308	15.67	336.93
16	6.4755	34.190	154.4	2.7505	12.43	424.81
17	8.1670	43.124	122.5	4.3746	9.857	535.62
18	10.300	54.388	97.10	6.9590	7.814	675.67
19	12.985	68.554	77.05	11.070	6.199	851.79
20	16.381	86.500	61.06	17.595	4.916	1074.11

Table X.—Data on Stranded Aluminium Wire.

Conductivity at 62 in the Matthiessen standard scale.

Number B. & S. gage.	Circular mils.	Diameters. Decimal parts of an inch.	Diameters. Nearest 32nd of an inch.	Weight in pounds. Bare. Per 1000 feet.	Weight in pounds. Bare. Per mile.	Weight in pounds. Triple braid insulated. Per 1000 feet.	Resistance in ohms at 70° F. per 1000 feet.
	1000000	1.152	1 5/32	920.	4858.	1406.	0.016726
	950000	1.125	1 1/8	874.	4617.	1337.	0.017606
	900000	1.092	1 3/32	828.	4374.	1268.	0.018585
	850000	1.062	1 1/16	782.	4131.	1199.	0.019679
	800000	1.035	1 1/32	736.	3888.	1129.	0.020907
	750000	0.996	1	690.	3645.	1060.	0.022301
	700000	0.963	31/32	644.	3402.	990.	0.023894
	650000	0.928	15/16	598.	3159.	921.	0.025734
	600000	0.891	29/32	552.	2916.	852.	0.027878
	550000	0.854	27/32	506.	2673.	782.	0.030411
	500000	0.814	13/16	460.	2430.	713.	0.033450
	450000	0.772	25/32	414.	2187.	644.	0.037170
	400000	0.725	23/32	368.	1944.	575.	0.041818
	350000	0.679	11/16	322.	1701.	506.	0.047789
	300000	0.621	5/8	276.	1458.	436.	0.055755
	250000	0.567	9/16	230.	1215.	366.	0.066905
0000	211600	0.522	17/32	195.	1028.	313.	0.079045
000	167805	0.464	15/32	155.	816.	253.	0.099675
00	133079	0.414	13/32	123.	647.	204.	0.12569
0	105534	0.368	3/8	97.	513.	165.	0.15849
1	83694	0.328	11/32	77.	407.	135.	0.19984
2	66373	0.291	9/32	61.	323.	112.	0.25200
3	52634	0.261	1/4	48.5	256.	93.5	0.31779
4	41742	0.231	7/32	38.5	203.	76.5	0.40069
5	33102	0.206	7/32	30.2	161.	56.0	0.50530
6	26250	0.180	3/16	24.1	128.	47.0	0.63720

Iron wire is not used for any ordinary transmission of electrical energy, except in cases of very small currents, as telephone, telegraph, signal, etc., and even here it is not as common as formerly. It has certain properties which would make it very satisfactory for such a purpose, but it also has serious faults.

If copper or aluminium could be brought to stand such high tension as iron, much would be gained. But such values as 60,000 pounds per square inch used for iron and 100,000 pounds per square inch used for steel cannot be equalled or even approached by either of these. Again, iron is exceedingly cheap compared to either of these other metals. As regards weight, although it has about 84 per cent. of the weight of copper, its conductivity is so much less than that of copper, that for equal conductivities it is much the heavier of the two. The ratio of resistances is about 1 to 6. This means that for equal conductivity an iron wire would weigh 5.04 times the given copper wire. Or, compared with aluminium the weights would be,

Weight of iron : weight of aluminium $=10.75 : 1$.

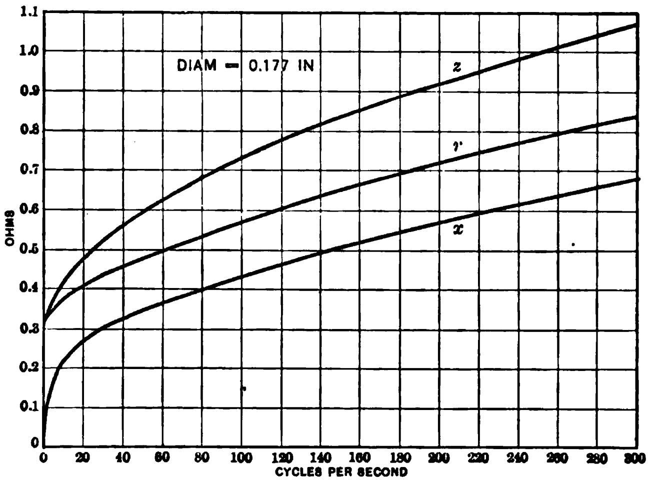


FIG. 2.—Skin effect with iron conductors. Diameter =0.177 inches.

Despite this handicap, special instances may arise where the extra strength of the iron will demand its use for certain long spans, as across a river. The most serious fault of iron for use as a conductor is that it is magnetic. The result is that with alternating currents the impedance is increased many fold over the ohmic resistance depending upon the frequency of the current, the size of the conductor, etc. In fact, the actual

effective resistance is increased due to the *skin effect* whereby the current density at the surface of the conductor is greater than the density in the interior of its cross-section. The effect is to reduce the cross-section of the conductor actually in use,

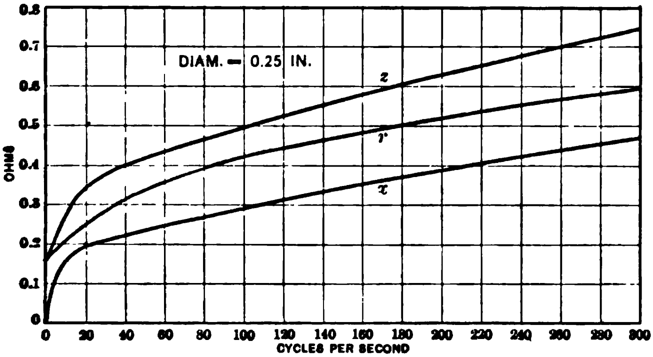


Fig. 3.—Skin effect with iron conductors. Diameter =0.250 inches.

that is, to increase the resistance, and is present even with copper conductors.

The effective resistance of the rail return of the Ballston line of the Schenectady Railway system was increased over the ohmic resistance in the ratio of 1 to 1.93 when alternating current

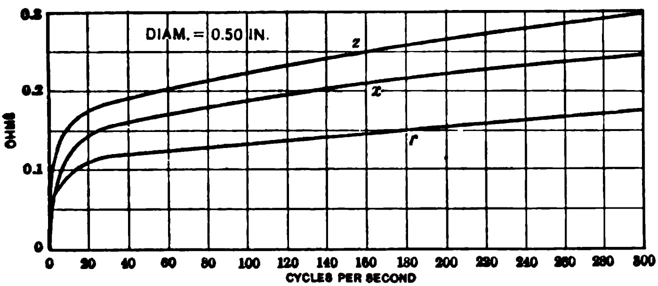


Fig. 4.—Skin effect with iron conductors. Diameter =0.50 inches.

series motors were put upon the cars and supplied with current at 25 cycles per second.

In an extended series of tests made in 1909 by Mr. C. M. Davis upon iron conductors of various sizes it is found that this effect

of increase of resistance (and also reactance and impedance) is very marked even with low frequencies. These increases are shown by curves in Figs. 2, 3, and 4, taken from Mr. Davis's report at Union College.

Similarly, by assuming that the conductor is replaced by a hollow one of equivalent resistance, having the same outer diameter and a thickness of shell d, Fig. 5 shows what may be

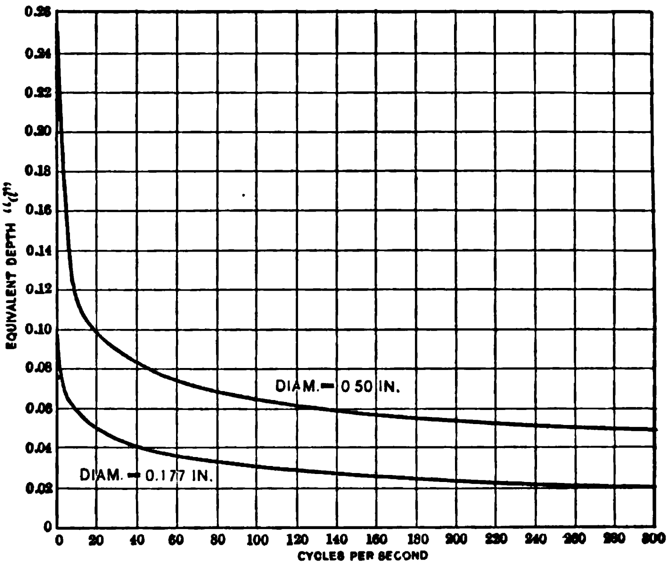


FIG. 5.—Equivalent depth of current penetration.

called the equivalent depth of penetration of the current in the conductors.

Comparing Fig. 6 with Figs. 2, 3, and 4, and remembering the differences in diameters, it is seen that stranding an iron conductor will reduce the effects above noted. Wherever an iron span is required, if current is of any large magnitude, the conductor should be stranded.

In case of an extra long span, where the copper wire has not sufficient strength and the iron wire has not sufficient conductivity, use may be made of *bimetallic wire*, an iron core within a

copper shell. As will be seen from the discussion upon skin effect, the change from copper core to iron core affects the resistance only slightly, but it furnishes a stronger wire.

There are many alloys in use as conductors, but they may be said to be of special application. Many are manufactured, each for the sake of some quality which makes it of great value under certain circumstances. That peculiar property may be strength, zero temperature coefficient, high resistance, etc., but these special features cannot be discussed at length at this time.

There are several different methods of using conductors as regards flexibility. One solid wire may be used where its size

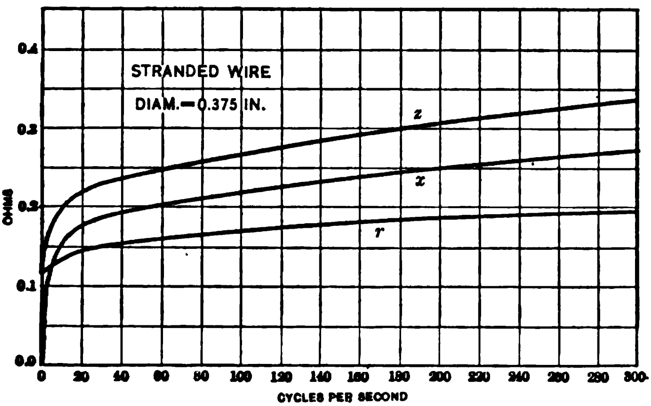


FIG. 6.—Skin effect with stranded iron conductor. Diameter = 0.375 inches.

is not sufficient to make it unwieldy and stiff. Where some flexibility is required the large conductor is replaced by several strands of wire of sizes 8 to 14 B. & S. gage. This gives only a partial relief and will not permit short bends. Where short turns must be made or the cable is to be handled or have its position changed repeatedly, smaller wires of sizes 14 to 20, B. & S. gage, must be used, keeping the total area of cross-section of metal as before. This increased pliability is obtained at an increased cost, for the small wires are more expensive per pound, there is much more work in forming the conductor either by twisting or braiding, and the increased diameter of the cable

due to subdivision demands more insulating material. As a consequence, the more flexible conductors are not used except where they are decidedly advantageous.

In aluminium cables, stranding is always practised as a mechanical protection to the cable itself and also as a relief to supports. It is manufactured down to an equivalent of No. 6 B. & S. gage, and has the properties shown in Table X, as already noted.

Insulation.—In the protection of circuits many materials are used for insulation. These different substances are not all equally successful under similar conditions, but each one may have a more or less particular application. Broadly speaking, however, there are some few materials which will satisfy all the requirements of ordinary service.

The conditions to be met include the harmful effects of moisture, change of temperature with extremes in either direction, salts and acids, injurious vapors, abrasion, etc., besides which there will be present in the material mechanical strength, high dielectric qualities, permanence, and more or less flexibility.

In securing these qualities, the best results are obtained by use of paper, rubber, or jute, cotton or hemp impregnated with some pitch or tar. Paper, oiled cambric, etc., are very frequently used in the heavier insulations and metallic sheaths are afterward provided for the sake of mechanical protection.

When rubber is used it is always *vulcanized.* This process consists of heating it to a temperature of about 150° C. and intimately mixing about 3 per cent. powdered sulphur with it. Owing to the presence of this sulphur, a copper wire so insulated must always be tinned in order to escape the corrosive attack otherwise resulting.

The vulcanization process gives the rubber durability and firmness, and makes it waterproof.

The conductor should be exactly central in any cable or the insulation is weaker upon one side than upon the other. Rubber should adhere to the copper if well manufactured.

There has been considerable discussion as to what simple tests may be made upon rubber insulation in order to determine its qualities. Many purchasers specify that the insulation shall contain at least 30 per cent. of Para rubber. Using a mixture following this specification and properly treating it by careful

vulcanization, etc., one may feel assured of good insulation. It is not necessary to pin one's faith only to Para rubber, however, for there are other rubbers of approximately the same grade.

The simplest tests of any particular value are the tests of strength, elasticity, voltage to puncture, and resistance per mile of conductor. A strip of the insulation taken from a conductor if of size large enough to be representative, should admit a tensile strain of 800 pounds per square inch without rupture. It should also be able to stand elongation to three or four times normal length without injury. Not only should the elongation be possible but when stretched to three times its length, it should promptly return to approximately its original length upon removal of the tension.

The potential test may be carried to 2.5 times normal or working potential. Excessive or long continued tests are apt to become injurious to the cable and develop incipient weaknesses, which, later, will be the cause of destruction of the insulation. It may be instructive to carry tests upon *samples* to their respective limits.

As regards the dielectric resistance per mile of conductor, this may be estimated by a formula suggested by Mr. E. W. Stevenson in the Trans. A. I. E. E. of 1906, namely:

Megohms per mile after 1 minute electrification at 60° F. $=6000(\log. D/d)$ where D is external diameter of the rubber and d is diameter of conductor. Definite values are often misleading, however, and more can be learned by comparison of several similar coils of wire or cable. Lack of uniformity here would indicate individual weaknesses which will sooner or later cause trouble.

Mr. W. S. Clark, in a paper before the A. I. E. E. in 1906, quotes the specifications of the Rubber Covered Wire Engineers' Association for 30 per cent. Rubber Insulating Compound. It is as follows:

Specifications 30 per cent. Rubber Insulating Compound.

Rubber-covered Wire Engineers' Association.

The compound shall contain not less than 30 per cent. by weight of fine dry Para rubber which has not previously been

used in rubber compounds. The composition of the remaining 70 per cent. shall be left to the discretion of the manufacturer.

Chemical.

The vulcanized rubber compound shall contain not more than 6 per cent. by weight of acetone extract. For this determination, the acetone extraction shall be carried on for 5 hours in a Soxhlet extractor, as improved by Dr. C. O. Weber.

Mechanical.

The rubber insulation shall be homogeneous in character, shall be placed concentrically about the conductor, and shall have a tensile strength of not less than 800 pounds per square inch.

A sample of vulcanized rubber compound, not less than 4 inches in length, shall be cut from the wire with a sharp knife held tangent to the copper. Marks shall be placed on the sample 2 inches apart. The sample shall be stretched until the marks are 6 inches apart and then immediately released; 1 minute after such release, the marks shall not be over 2 3/8 inches apart. The sample shall then be stretched until the marks are 9 inches apart before breaking.

For the purpose of these tests, care must be used in cutting to obtain a proper sample, and the manufacturer shall not be responsible for results obtained from samples imperfectly cut.

Electrical.

Each and every length of conductor shall comply with the requirements given in the following table. The tests shall be made at the works of the manufacturer when the conductor is covered with vulcanized rubber, and before the application of other coverings than tape or braid.

Tests shall be made after at least 12 hours' submersion in water and while still immersed. The voltage specified shall be applied for 5 minutes. The insulation test shall follow the voltage test, shall be made with a battery of not less than 100 nor more than 500 volts, and the reading shall be taken after 1 minute's electrification. Where tests for acceptance are made by the purchaser on his own premises, such tests shall be made within 10 days of receipt of wire or cable by purchaser.

Table XI.—Insulation Resistance.

30 per cent. rubber compound. Megohms per mile. 60° F.
One minute-electrification.

	Thickness of insulation.								
	3/64	2/32	5/64	3/32	7/64	4/32	5/32	6/32	7/32
1,000,000 cir. mils					200	210	235	265	300
900,000 cir. mils					235	250	280	315	360
800,000 cir. mils					270	290	325	370	[illegible]
700,000 cir. mils					305	325	370	420	[illegible]
600,000 cir. mils					340	365	420	470	540
500,000 cir. mils				350	375	405	465	525	600
400,000 cir. mils				390	420	450	530	600	670
300,000 cir. mils				430	470	505	590	680	750
250,000 cir. mils				455	500	540	630	720	810
4/0 stranded			440	480	520	565	660	750	840
3/0 stranded			450	490	535	580	675	770	860
2/0 stranded			460	500	545	590	690	790	880
1/0 stranded			490	540	590	650	760	860	950
1 solid			520	580	635	700	830	950	1,060
2 solid		500	550	615	680	750	900	1,040	1,160
3 solid		530	585	650	715	795	940	1,080	1,210
4 solid		560	620	690	750	830	990	1,130	1,260
5 solid		590	655	720	790	870	1,040	1,180	1,300
6 solid		620	690	760	840	920	1,100	1,230	1,350
8 solid	610	710	800	880	985	1,060	1,240	1,370	1,490
9 solid	650	750	850	940	1,050	1,130	1,310	1,440	1,560
10 solid	690	795	905	1,000	1,120	1,200	1,380	1,510	1,620
12 solid	750	870	990	1,110	1,250	1,370	1,540	1,680	1,790
14 solid	800	930	1,060	1,200	1,340	1,470	1,640	1,780	1,890

30 per cent. rubber compound. Voltage test for 5 minutes.
For 30-minute test take 80 per cent. of these figures.

Size.	Thickness of Insulation.											
	3/64	4/64	5/64	6/64	7/64	4/32	5/32	6/32	7/32	8/32	9/32	10/32
1,000,000 to 550,000					4000	6000	10000	14000	18000	22000	26000	30000
500,000 to 250,000				4000	6000	8000	12000	16000	20000	24000	28000	32000
4/0 to 1			4000	6000	8000	10000	14000	18000	22000	26000	30000	34000
2 to 7		4000	6000	8000	10000	12000	16000	20000	24000	28000	32000	36000
8 to 14	3000	5000	7000	9000	11000	13000	17000	21000	25000			

Inspection.

The purchaser may send to the works of the manufacturer a representative who shall be afforded all necessary facilities to make the above specified electrical and mechanical tests, and also to assure himself that the 30 per cent. of rubber above specified is actually put into the compound; but he shall not be privileged to inquire what ingredients are used to make up the remaining 70 per cent. of the compound.

The best rubber compounds are expensive and wherever it is possible they are often replaced by cheaper materials. Due to reduced intrinsic value it is possible in many cases to equal its insulating value by use of a greater amount of material, thus making a cheaper cable and one just as satisfactory and durable. In fact, the life of rubber compounds may be exceeded by that of paper or varnished cambric.

With varnished cambric the copper is first given a layer of paper, cloth, or rubber to avoid chemical action. The varnished cambric is then applied in tapings between which are placed thin coatings of plastic material which will permit adjacent layers of the cambric to slide upon each other and return to place again as the cable is bent and straightened. This excludes air and moisture as well. The core is then given cotton braiding and weather proofing for outside work or asbestos braiding and fire proofing for station wiring, or taping and lead sheath for such installations as may demand it. These cables may be bent to a radius equal to six times their own diameter. Transformer cooling oil or that used in oil switches does not injure the insulation.

One of the strong points of this insulation is that it will not deteriorate so rapidly as either paper or rubber if the protecting coat of lead, asbestos, etc., is injured by electrolysis, abrasion, or otherwise. In handling and installing paper protected cables great care must be taken to keep all cable ends sealed against absorption of moisture.

The general make-up of cables is shown in Figs. 7 to 10. Tables XII, XIII, and XIV, respectively, give data upon the constants per mile of cable, the current capacity and the testing voltages to be used for varnished cambric cables.

Table XII.—Approximate Ohmic Resistance and Impedance of three Conductor Cables.

Size.	Resistance ohms per mile.	Impedance ohms per mile. Working voltage. 3000.	5000.	7000.	10000.	15000.	20000
2	0.850	0.858	0.859	0.863	0.867	0.872	0.884
1	0.674	0.692	0.696	0.700	0.706	0.712	0.724
0	0.535	0.545	0.547	0.552	0.558	0.565	0.580
00	0.424	0.436	0.439	0.444	0.452	0.460	0.478
000	0.336	0.352	0.352	0.357	0.365	0.374	0.396
0000	0.267	0.280	0.283	0.288	0.296	0.306	0.332
250,000	0.227	0.245	0.245	0.252	0.261	0.272	0.299
300,000	0.188	0.210	0.210	0.217	0.227	0.241	0.270
350,000	0.161	0.187	0.187	0.194	0.204	0.217	0.250
400,000	0.141	0.166	0.166	0.174	0.185	0.199	0.234
450,000	0.127	0.148	0.148	0.156	0.167	0.182	0.221
500,000	0.113	0.137	0.137	0.144	0.156	0.172	0.212

Based on pure copper at 75° F. with an allowance of 3 per cent. for spiral path of conductors, 60 cycles per second, and standard thickness of varnished cambric insulation.

Values are practically the same for other types of insulation.

NOTE.—*These figures are approximately correct for* 98 *per cent. conductivity copper at* 65° *F.*

Table XIII.—Current Carrying Capacity of Insulated Cables.

Initial Temperature, 20° C.

Size of cable in circular mils.	National Electric Code 1907. Rubber.	Low tension cable single conductor. Rubber 30° C. rise. Amperes.	Low tension cable single conductor. Var. cam. or paper 60° C. rise. Amperes	High tension cable three conductor. Rubber & var. cam. 30° C. rise. Paper 35° C. rise. Amperes on each conductor.
2,000,000	1050	1400	1750	
1,500,000	850	1200	1500	
1,000,000	650	900	1150	
750,000	525	750	900	
500,000	390	550	660	440
400,000	330	460	560	360
300,000	270	370	450	290
250,000	235	320	390	250
200,000	200	270	310	210
150,000	160	220	260	175
125,000	140	180	210	140
100,000	120	160	190	125
80,000	104	140	165	110
60,000	82	110	130	85
40,000	63	75	90	60
6 B. & S. solid	46	50	60	40
8 B. & S. solid	33	30	36	24
10B. & S. solid	24	20	24	16

The dividing point between low tension and high tension is taken as 3000 volts.

Table XIV.—Working and Test Voltages.

Kilovolts working pressure.	Sizes.	Thickness insulation.	Test in kilovolts. At factory. 5 min.	30 min.	60 min.	After installation. 5 min.	30 min.	60 min.
1	6–2	1/16	2.5	2	1.6	2	1.6	1.3
1	1–0000	5/64	2.5	2	1.6	2	1.6	1.3
1	250,000–500,000	3/32	2.5	2	1.6	2	1.6	1.3
1	550,000–1,000,000	7/64	2.5	2	1.6	2	1.6	1.3
1	1,100,000 and over	4/32	2.5	2	1.6	2	1.6	1.3
2	6–0000	3/32	5.0	4	3.2	4	3.2	2.6
2	250,000–500,000	7/64	5.0	4	3.2	4	3.2	2.6
2	550,000–2,000,000	4/32	5.0	4	3.2	4	3.2	2.6
3	All sizes	9/64	7.5	6	4.2	6	4.8	3.8
4	All sizes	5/32	10.0	8	6.4	8	6.4	5.1
5	All sizes	6/32	12.5	10	8.0	10	8.0	6.4
6	All sizes	7/32	15.0	12	9.6	12	9.6	7.7
7	All sizes	8/32	17.5	14	11.2	14	11.2	9.0
8	All sizes	17/64	20.0	16	12.8	16	12.8	10.2
9	All sizes	9/32	22.5	18	14.4	18	14.4	11.5
10	All sizes	10/32	25.0	20	16.0	20	16.0	12.8
11	All sizes	11/32	27.5	22	17.6	22	17.6	14.1
12	All sizes	12/32	30.0	24	19.2	24	19.2	15.4
13	All sizes	12/32	32.5	26	20.8	26	20.8	16.6
14	All sizes	13/32	35.0	28	22.4	28	22.4	17.9
15	All sizes	13/32	37.5	30	24.0	30	24.0	19.2
16	All sizes	14/32	40.0	32	25.6	32	25.6	20.5
17	All sizes	14/32	42.5	34	27.2	34	27.2	21.7
18	All sizes	15/32	45.0	36	28.8	36	28.8	23.0
19	All sizes	15/32	47.5	38	30.4	38	30.4	24.3
20	All sizes	16/32	50.0	40	32.0	40	32.0	25.5
21	All sizes	16/32	52.5	42	33.6	42	33.6	26.8
22	All sizes	17/32	55.0	44	35.2	44	35.2	28.1
23	All sizes	17/32	57.5	46	36.8	46	36.8	29.4
24	All sizes	18/32	60.0	48	38.4	48	38.4	30.7
25	All sizes	18/32	62.5	50	40.0	50	40.0	31.9

"Above working voltages are based on all conductors of the circuit being insulated. For d.c. 600-volt railway single-conductor, leaded cables, use 2000 volt class. For 3-phase "Y" connected circuits with grounded

neutral with three conductor cables, thickness of insulation between conductors and ground need be only 7/10 of that between conductors. Tests on such cable in proportion to thickness of insulation: Example, 3-phase, 12000-volt circuit "Y", neutral grounded, insulation on each conductor 6/32 in. (total between conductors 12/32 in.), outer belt 3/32 in. (total 9/32 in.); test pressure at factory for 5 minutes between conductors 30,000 volts, each conductor to earth 22,500 volts. For mechanical reasons, thickness of insulation on individual conductors of 3-conductor cables 3,000 volts and less is made somewhat greater than required by working pressure on some sizes."

Paper is an excellent insulator and gives good satisfaction when used in cable protection. Its use is becoming more prevalent owing to its desirable properties. It has durability, high dielectric strength, some flexibility and low specific inductive capacity. It must be carefully guarded from moisture by impregnating it with paraffin, resin, oil or other compound and

FIG. 7.—Two-conductor 1,000,000-circular-mil concentric cable.

FIG. 8.—6 B. & S. G., flat, twin, leaded cable.

FIG. 9.—Three-conductor number 00 leaded cable.

FIG. 10.—Three-conductor 250,000-circular-mil armored cable.

sheathing it preferably in lead. This lead covering is one continuous body and is formed directly upon the cable by passing the cable through a vessel containing molten lead. As the cable is withdrawn through an opening, the lead is forced out with it by hydraulic pressure and forms a seamless and continuous coating.

Gutta-percha is a natural gum which is largely used in insulation also. Its dielectric strength is about equal to that of rubber. It is necessary, however, to protect it from the air or

it will quickly oxidize and lose its insulating qualities as well as its elasticity. Consequently, its most common use is in submarine cables where it is well covered by wire or steel ribbon over jute, in turn being covered by a jute-asphalt coating to protect the iron from corrosion. Again, it softens with small temperature rises and must be kept cool. Such a cable, if broken under water, will not absorb water as every attempt is made to form the insulation and conductor into a solid mass. Oils are, however, injurious, and such cables must not be used in connection with oil-cooled machines.

As noted in previous paragraphs, asbestos is used for various qualities, including stability, heat-resistance, etc.

Paraffin is used as a filler for paper, cloth, etc.

While these and many other materials are used in the insulation of conductors, the most economical usage is to grade the materials by their specific inductive capacity and use them from the conductor outward, arranged in such an order that their specific inductive capacities vary inversely as the distances from the center. The result of this grading is to establish a more uniform potential gradient throughout the covering with no greater tendency to puncture at the surface of the conductor than at the outer coating. This may be made clearer by likening the layers of insulation to successive capacities in series with each other. The greatest potential strain will occur across the smallest capacity. In a uniform covering the potential gradient will be represented by the expression

$$\frac{de}{d\rho} = \frac{0.434\,E}{\rho \log R/r} = \text{potential gradient},$$

where E equals the total potential strain; r is the radius of the conductor; R is the outer radius of the insulation and ρ is the radius to the point whose potential gradient is desired. This means that the potential gradient is inversely proportional to the radial distance ρ. If, then, we place in contact with the conductor the insulation having the greater specific inductive capacity, the strain across it will be less than it would for low specific inductive capacity, as it corresponds to the greater capacity in the comparison above made.

It has been proposed to use for these successive layers paper impregnated with different substances, as oil, resin, ozokerite, paraffin, pitch, etc., thereby securing specific inductive capacities of 3.3 to 4.8. It would seem possible to secure greater variation by combinations of paper insulation and rubber insulation as the latter, mixed with different quantities of sulphur, talc, minium, zinc oxid, carbonate of lime, etc., will give specific inductive capacities of 4 to 6.10, and still have good dielectric strength. In fact, by letting the dielectric properties suffer rather seriously, the use of gypsum, lime, and baryta with rubber substitutes will give specific inductive capacities of 10 to 12. So great is the drop in dielectric strength and the length of life, however, that the use of such low-grade insulation is not permissible.

The variation of specific inductive capacity of numerous insulating materials is given in Table XV as suggestive of the ordinary limits encountered. They are wide enough, however, to allow considerable latitude, if suitable means are developed for the combining of some of these substances in one cable covering.

Table XV.—Specific Inductive Capacity.

Paper	2.00
Rubber—pure	2.12
Rubber—vulcanized	3.00
Ozokerite	2.13
Paraffin	2.00– 2.32
Resin	2.00– 3.00
Shellac	2.74– 3.67
Sulphur	2.88– 3.21
Paper cables	3.30– 4.80
Gutta percha	3.30– 4.90
Rubber cables (Sulphur, talc, minium, zinc oxid, carbonate of lime)	4.00– 6.10
Porcelain	4.40
Castor oil	4.60– 4.80
Mica	5.00– 7.00
Rubber cables (gypsum, lime, baryta, rubber substitutes)	10.00–12.00

CHAPTER II.

LINE INSULATORS.

Types of Insulators.—The first transmission lines requiring insulation from the return conductors were telegraph lines. The separation was accomplished by wooden supports. Wet weather introduced the now well-known difficulties attendant upon failure of insulation and it became necessary to use porcelain, pottery and glass insulators. The result has been the gradual development of the ordinary glass telegraph insulator. When the transmission of power became a feature of electrical engineering practice, the natural step was to use the same insulators as were then manufactured for telegraph and telephone service.

The growth of the art has been rapid and year by year, during the last two decades, enormous strides have been made in the voltages used, the amount of power transmitted, the distances covered, etc. This has, likewise, required an accompanying advance in every detail pertaining thereto.

During this time, it has become recognized that there are numerous things to be accomplished by the insulator beside that important feature of isolation of the conducting strand. The materials used must be strong mechanically, of minimum permissible weight, etc. Glass had the dielectric strength required when it was in its solid form, but it needed to be toughened to meet other requirements. Porcelain has also been improved in quality and grade. Papers before the International Electrical Congress at St. Louis have shown the development to that time by a series of illustrations here reproduced.

The telegraph line insulator appropriated by pioneers in power work is shown in Fig. 11. It was used in 1890 for a 3,000-volt line in a Colorado mining locality at an elevation of 12,000 feet above sea level. Its success was marked.

In 1891, the Frankfort-Lauffen experiments were made in Germany using a porcelain insulator with an inwardly upturned

Fig. 11

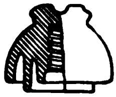


Fig. 12

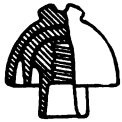


Fig 13

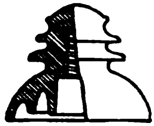


Fig. 14

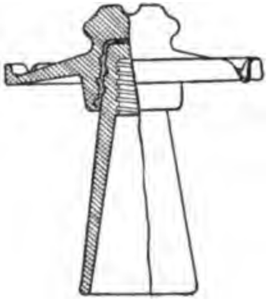


Fig. 15

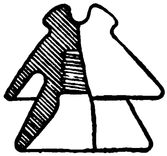


Fig. 16

Fig. 17

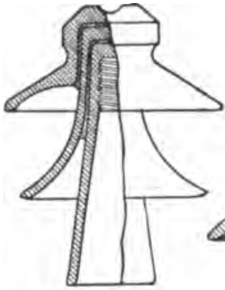


Fig. 18

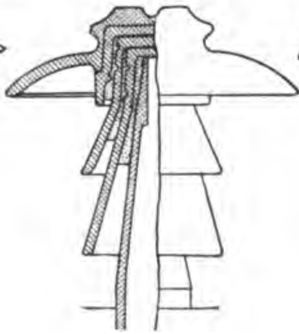


Fig. 19

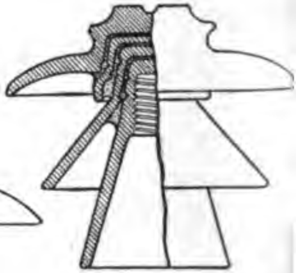


Fig. 20

FIG. 11.—Telegraph insulator. FIG. 12.—Triple petticoat insulator. FIG. 13.—Glass filled insulator. FIG. 14.—Provo insulator. FIG. 15.—Mushroom type insulator. FIG. 16.—Niagara type insulator. FIG. 17.—Missouri River Power Co. insulator. FIG. 18.—Shawinigan Falls insulator. FIG. 19.—Guanajuato insulator. FIG. 20.—60,000-volt insulator.

petticoat which formed a cup for oil. This was designed to lessen the liability to disruption over the surface of the insulator due to leakage. This suggestion was taken up in this country and elsewhere and further types tried. It has been found, however, that their use is not warranted and no dependence is now placed upon this type. Its failure is due, not to any fault in principle, but to a gradual accumulation of insects in the oil.

Figure 12 illustrates a type of insulator used on pressures up to 16,000 volts in 1897.

Due to failure of porcelain insulators it was determined to obviate the difficulty of porosity of the insulator body by making it in several pieces and glazing them together (Fig. 13). Moreover, the pieces were built upon the potter's wheel instead of being pressed or molded. In this form the inner peticoat is long, as a protection to the pin.

1898 saw the beginning of 40,000-volt transmission at Provo, Utah, with glass insulators shown in Fig. 14.

In 1900, practice had reached 60,000 volts and the insulator used had become the mushroom type (Fig. 15). It consists of two pieces, a long petticoat covering the pin and a large flat top with guttered edge. The petticoat was made of glass and the head was of porcelain. They were fastened together by sulphur.

The Niagara type (Fig. 16) is a compromise between the horizontal petticoat and the vertical petticoat.

The Missouri River Power Company in 1901 installed a two-part insulator, shown in Fig. 17, consisting of an insulator proper with petticoats and a sleeve for pin protection.

A three-piece porcelain insulator shown in Fig. 18 was used at 50,000 volts in the Shawinigan Falls installation. It will be noted that the head of each piece is closed, thus adding to the dielectric strength in contra-distinction to Fig. 17. Here the parts are cemented together by Portland cement.

A further growth of insulator is indicated in Fig. 19, a type used in Guanajuato, Mexico. The cut shows that a metal pin is used, being cemented in place. This type, as well as that shown in Fig. 20, is used at 60,000 volts.

Beyond these sizes, pin-supported insulators become bulky and heavy. They are built, now-a-days, for use up to voltages as high as about 70,000.

Figure 21 shows one type rated at 70,000 volts. The diameter is 18 inches; the height is 14 inches. It weighs about 45 pounds.

There are, besides these general types, many more or less special types designed to meet every requirement.

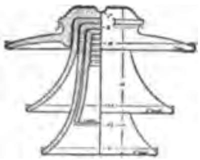


FIG. 21.—70,000-volt insulator.

FIG. 22.—Feeder insulator.

When low-voltage feeders are to be supported, a large top groove is needed as is shown in Fig. 22. The material of this particular insulator is glass, which, in fact, is generally used for such work.

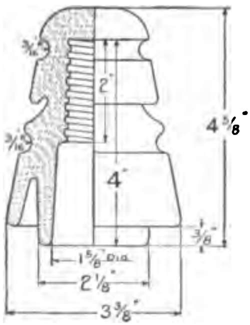


FIG. 23.—Telephone transposition insulator.

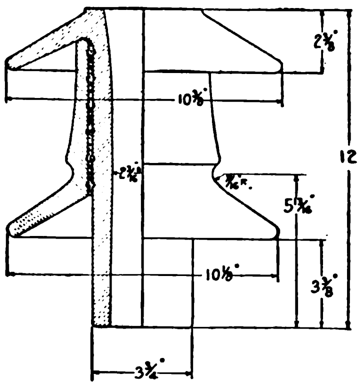


FIG. 24.—Strain insulator.

While heavy work requires that the conductor shall lie in a top groove central to the insulator body, lighter or special work frequently is best handled by side grooves. This is necessary, for example, in telephone transposition. Either glass or porcelain may be used and Fig. 23 is typical of the forms employed.

Dead-ending the line is accomplished by strain insulators which are supported above and below by cross arms. Here it is necessary that the pin shall pass upward through the top of the insulator, which may be of one piece or two pieces as is required by its size. Figure 24 gives dimensions of a two-piece porcelain strain pin insulator intended for use on 35,000-volt circuits, hence it will accomodate only a comparatively small conductor. It weighs about 16 pounds. This type is used also for dead-ending heavy conductor cables either directly or by the interposition of stranded steel wire cables or metal straps, in which case larger grooves are needed.

FIG. 25.—Link type strain insulator.

More recently, there have been installed several variations of the type known as the *Link insulator*. It is a form in which several units may be used, being held together by cast links or flexible material, as cable, etc. Each unit has two openings for these successive links to enter, so formed that the ends of the cable thread through each other but are separated by solid material. Figures 25 and 26 will show their construction quite fully. They are 7.25 inches to 10 inches in diameter and are rated at from 11,000 volts to 25,000 volts per unit. They are made in both the strain type and the suspension type. Figures

FIG. 26.—Link type strain insulator.

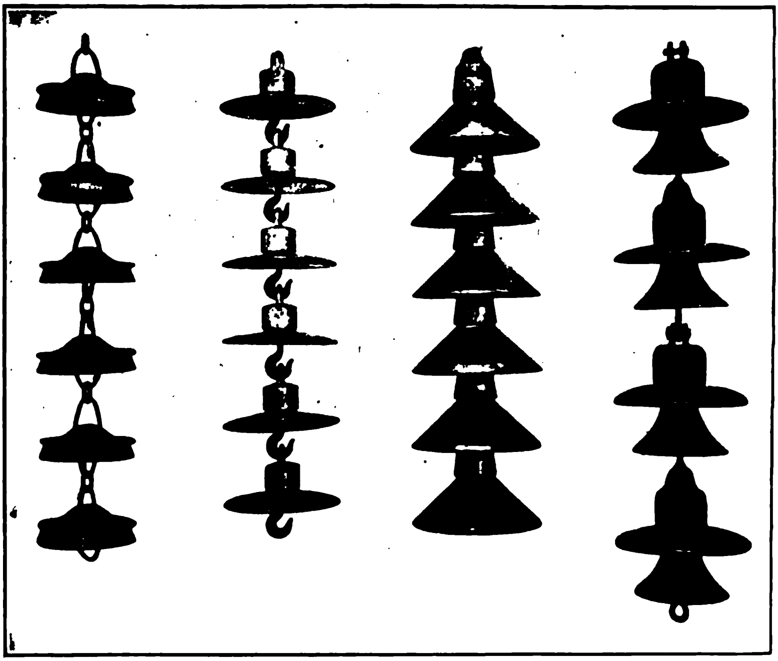


FIG. 27.—General Electric, Thomas, Locke, and Lima suspension insulators.

25 and 26 show the strain type for use in horizontal position as indicated in the illustration, and Fig. 27 illustrates, in succession, the General Electric, Thomas, Locke, and Lima suspension insu-

FIG. 28.—Link type suspension insulator.

FIG. 29.—Link type strain insulator in position.

lators. Figure 28 shows a lower voltage suspension type, weighing 4.25 pounds, made by the Ohio Brass Co. It will be noted that they are all so flanged that there are no cups for

retaining moisture. Figure 29 shows the strain type in position. So successful is this type that it is taking the place of the old pin type in all high-voltage work now being installed. It has been installed and is in successful operation upon a 110,000-volt transmission line of the Grand Rapids and Muskegon Power Company, and other lines.

Mr. H. W. Buck states that the advantages of this link type of insulator are:

1. It is cheap and easy to manufacture and will replace large, heavy, expensive insulators.

2. The pin is eliminated on a cross arm, doing away with the consequent severe torsional strains.

3. The insulation may be increased very easily.

4. The strain type allows no accumulation of dirt.

5. A standard type may be adopted, varying the number of units for different voltages.

6. Destruction of one unit does not destroy the insulator and the unit is easily replaced.

7. A lightning discharge is more likely to strike the tower than the line, the former being the higher.

8. The flexibility at the point of support lessens the danger of breaking at the tower.

The enumeration of the preceding features of common practice indicate that there are many things demanded of the insulator.

1. High dielectric strength requires that material selected shall be homogeneous.

2. Mechanical strength is attained by toughness of material as well as quantity used and proportion of parts.

3. The shortest path from tie wire to pin or cross arm must give sufficient length to prevent arcing.

4. The surface path from tie wire to pin must be long enough to prevent surface leakage.

5. The material must be non-hygroscopic, non-absorbent, and durable.

6. As far as possible the surface should be protected from rainfall, fog, dust, salt, etc.

7. The charging current must be small.

8. The heating due to charging and leakage currents must be small.

9. Strains must be carried centrally, without shearing stresses.

Materials Used.—In order to accomplish these results the material must be of high-grade glass or porcelain. Glass is hardly ever used for work above 25,000 volts. It has a very high dielectric strength, the potash glasses being better in this respect than the soda glasses. It is more hygroscopic than porcelain, however. The specific inductive capacity varies from 2.8 to 9.9. When once softened by heat of an arcing discharge the dielectric strength falls off remarkably and at high temperatures it may be considered as a conductor. Nevertheless, such an accidental occurrence is highly improbable except under most extraordinary circumstances, including both large current and high voltage, a condition where other considerations would probably have already restricted the choice of insulators to porcelain.

Pieces made of glass are easily inspected for cracks, bubbles or other imperfections, as they are always made transparent. This also makes all recesses light and insects are not harbored. This is especially commendable for use in small insulators where porcelain would give dark corners. It may be toughened by annealing. One very serious fault of glass is its brittleness. This has not been overcome and any slight blow or sudden strain is liable to abruptly terminate its usefulness. The surface is also roughened by exposure, thus aiding in the collection of dirt.

Porcelain is probably the only practical material for line insulators, which in some form or other can be relied upon for all voltages and currents now used or contemplated. There are several kinds of porcelain manufactured, not all of them being useful to the engineer.

The China porcelain is a mixture of kaolin with a natural glass. French porcelain contains an artificial glass. There is more of the glass present in the French mixture. This glass serves the purpose of fusing and filling all the openings that would otherwise exist between the fine particles of the clay. The porcelain becomes, then, non-porous.

It will readily be understood that the more glass there is in the mixture, the more fragile is the product. When, however, the proportion of glass has become great enough to fill all the interstices, its purpose is accomplished, so far as insulators are

concerned. Greater percentages of glass will add to the frailty of the finished piece and also make the insulator more fusible.

The successful manufacture of the porcelain which has just enough glass (called "hard paste" in contradistinction to the "soft paste" or French product) is a rather delicate matter. It means that the molded piece before being heated to the fusing point of the glass must have no cracks or cavities, for they cannot fuse shut, as is possible in the soft paste mixture. The fusing point is higher than it is for soft paste. So that, all told, the materials used are more expensive and the whole process is more difficult and more refined. Unfortunately, as it is a hard matter to distinguish between the different grades of the finished product, the natural tendency is to lessen the cost by introducing a little more of the glass than is actually required.

In fusing, the body of the piece shrinks about 15 per cent. due to the driving out of the moisture. This shrinkage may cause stresses in portions of different thicknesses as it does in glass. Faults of this kind may appear during the firing or even during the molding, especially if the latter is done by compression. Large pieces are generally formed by hand in a mold upon a potter's wheel. This is easily accomplished, as the inner cavities are generally large enough for easy manipulation. Of course, this adds very materially to the expense.

Beside the fusing of the mass into a solid homogeneous body, differentiating the product from porous pottery, the surface of the insulator must be glazed to make it smooth and non-hygroscopic. This glaze must not crack with changes of temperature or roughen upon exposure to weather. The glazing permits addition of coloring matter to render the insulator less conspicuous, an object well worth attention, as a large white insulator is a very attractive mark for the rifles of reckless or thoughtless hunters. Brown is a popular choice, though gray, slate, green-slate, or yellow are perhaps less prominent, but lack uniformity of coloring.

Colored glazes are more easily regulated if the "soft fire" glazes are permitted. They are not satisfactory from the engineer's standpoint as, being a lead glass, they are more fusible and less durable than the "hard fire" glazes.

The lines shown in Fig. 30 indicate what is meant by the

"striking distance," or "rupture distance," and the "leakage distance." The sum of the lines A, B, C, will be the striking distance in wet weather, but in dry weather with a clean insulator top, this distance will be increased by the length of the path from the tie wire to the edge of the upper umbrella shell. If the vertical distance between the conductor and the edge of the umbrella is less than the distance from tie wire to umbrella edge, the former should be used instead of the latter.

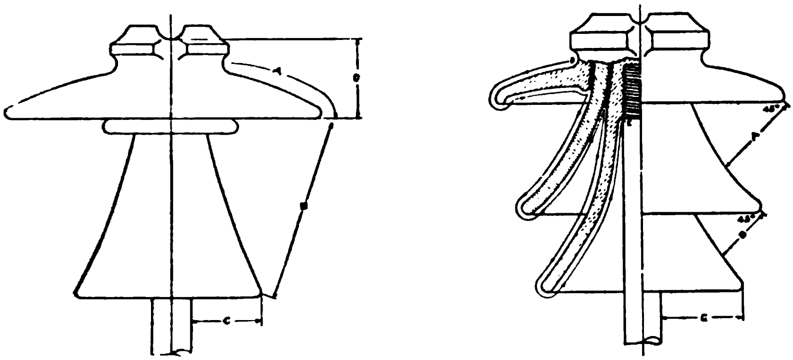


FIG. 30.—Leakage and rupture paths.

The proper design of the insulator takes cognizance of the spacing of the petticoats for small capacity effects as well as the proper angles for their projection in order to protect the lower ones from rainfall, etc.

Due to shearing stress upon the insulator itself and also the increased torsional strain upon the pin and cross arm resulting therefrom, no large insulator should have a top groove located other than centrally. The use of side grooves or displaced top grooves is not customary for such service (except, of course, upon curves).

The usual practice in insulating conductors where they enter buildings will be discussed at a later point. The insulators used for this purpose, however, vary widely. They are tubular, of diameters varying from loosely fitting coverings to 20 inches or more. They are used singly or cemented together in "nests" in order to increase the leakage path. Corrugated surfaces furnish the same feature. They are never designed to take the strain or

pull of the conductor, but are looked upon merely as a sheath or sleeve for insulating purposes.

In a way, the passing of a cable through an inner wall or a floor may be treated about the same as through an outer wall, except that weather conditions do not limit the size of the opening permitted. For low voltages, tubes may be had specially designed for floor use.

Fig. 31.—High tension oil filled bushing.

Insulating bushings used in entering transformer tanks, etc., are especially in the care of the manufacturer of such apparatus. However, it is sometimes necessary for the transmission or construction engineer to utilize similar products. Late forms proposed include the use of the so-called *condenser type* of bushing. It is built up of successive layers of insulating material, as varnished cambric, etc., at intervals in its construction single thin layers of conducting material being inserted, as tin foil. The attempt is made thus to change the potential gradient through the bushing as has been already discussed in connection with the insulation of cables.

Another form is a built-up hollow composition cylinder with caps at each end. The barrel surface of the cylinder is flanged with varnished annular rings of sufficient depth to give long leakage path from the central point of support to the end cap. The conductor is a heavy rod tying the two caps together under tension and the cylinder is filled with insulating oil, circulating through concentric cylinders of pressboard (Fig. 31). These bushings have been built to stand test voltages of over 300,000 volts. This type is also proposed for wall outlets.

Testing of Insulators.—In order to test the dielectric strength of an insulator it should be inverted and set deep enough into

salt water to cover well the head to the point occupied by the tie wire. Salt water is then to be poured into the pin hole. Terminals of a high potential circuit should constitute the grounded metal containing dish of the water into which the head is plunged and a metal rod inserted in the water in the pin hole. The testing voltage should be maintained from 1 minute to several minutes depending upon its relation to working voltage. The ratio between testing potential and normal potential varies from about 5 for low voltages down to 2 for very high voltages. This latter is a low factor of safety, but probably the insulator is required to run at a condition nearer its test value than any other part of the system. This is to be deplored, but probably with the pin type of insulator it is unavoidable.

If the insulator is of more than one piece it is advisable to similarly test each portion separately at a voltage proportional to the estimated line voltage for that part. Then the insulator should be assembled and the whole tested as above. This assures good reliable parts as well as a satisfactory unit. Every porcelain insulator should be given complete tests. Glass can receive a fairly close inspection for flaws and dimensions (thickness especially to be noted), and hence it is permissible to test a representative lot from a shipment and depend upon inspection of the remainder.

Strain insulators used for dead-ending are preferably tested by inserting a metal rod or tube in the assembled unit and resting the whole upon a metal plate to represent the wet cross arm. Then the testing voltage is applied to the rod and to the cable groove.

Wall insulators, bushings, etc., are similarly treated by putting a metal band around the outer periphery but omitting the metal plate.

These tests will probably also indicate whether or not there is much surface leakage, by visible discharge or by heating.

For testing rupture voltage, the insulator should be mounted upon a pin and support a conductor. Then voltage will be applied between these two in proportion to line-to-neutral voltage. It is also advisable to try two such upon one arm and put a correspondingly larger voltage across them. This will approximate the conditions met with in practice. Such tests need be made only upon a portion of those purchased.

Weather tests are indefinite in results. Certain things can be accomplished quite satisfactorily, but other requirements are in no wise met by laboratory tests. The precipitation test is recommended. The Locke Insulator Co. performs this test in a darkened room where discharge is more quickly discernible. Nozzles throwing a fine spray are allowed to play upon the insulator which is mounted by a metal pin upon a regular cross arm. About a 45-degree angle is maintained. High voltage is applied between the grounded cross arm and a conductor carried in the top groove. The voltage is raised slowly till arcing occurs. This is considered as a rough determination of the integrity of the insulator under any condition of precipitation. The conditions used are:

Precipitation..........	1 inch in 5 minutes.
Angle of precipitation..	45 degrees.
Water pressure........	40 pounds per square inch.
Distance of nozzle from insulator............	30 inches.

Pin long enough to give rise to discharge to pin rather than arm.

Insulators should not be cold enough to condense moisture.

When the spray is allowed to strike up under the petticoats, results obtained are much lower. Thus far, storm tests are very satisfactory, but there are other conditions not attainable. Such influences as dust storms, fogs, salt storms of the coasts, etc., are wholly problematical except that they are well recognized sources of trouble. It is necessary, therefore, in selecting insulators for a certain line, to know the locality and its climatic features as well as the voltage to be used.

There is no satisfactory method of testing an insulator for its mechanical or crushing strength. The irregularity of its outline is such that strains are not uniform and results obtained by attemptedly similar loadings would vary widely. Comparative dimensions are noted and this is allowed to take the place of strength tests.

CHAPTER III.

POLES AND TOWERS.

The supporting of the conductors of a transmission line is a mechanical proposition of prime importance as well as being of no mean proportions. It demands close attention to every detail of construction, etc., in order that it may be successfully accomplished at an economical figure.

As regards the poles to be used, by far the greatest part of all transmission lines are supported upon wooden poles. Telephone and telegraph poles are invariably wooden and they constitute a total scores of times the number used in power transmission. Iron is a standard material for poles, also, being used in various forms. Concrete poles are not uncommon and have certain commendable features. When the construction becomes very heavy the wooden poles may be grouped or they may give place to the steel tower, patterned after a windmill tower in many respects. There are no other suitable materials for this work.

The wood used for poles depends upon the locality, which greatly influences relative costs. There are serious differences in their characteristics, however, and the use of a pine pole in a certain locality does not indicate that it is the most satisfactory material to be had from the standpoint of durability and strength. It does mean that it is enough cheaper than the best woods so that its use is warranted. Probably the greatest use is made of cedar and chestnut. In fact, of the 3,750,000 poles purchased in 1909 for telegraph, telephone, and power service, 65 per cent. were cedar, 16 per cent. were chestnut and 6.3 per cent. were oak. The percentage of chestnut decreased from 28 per cent. of the total number used in 1906. Pines, long leaf, short leaf and loblolly, cypress, catalpa, juniper, tamarack, spruce, etc., are common. Some redwood is used upon the Pacific coast.

Durability, or life of a pole, depends upon various things beside the tree species used. A sawed pole is shorter of life than

is a pole in its natural state stripped of bark. The capillary cavities are not opened to absorption of moisture in the latter case to the extent that they are in the former. Old timber is more generally apt to decay than is young timber which contains more sap wood. In the pines, the slow-growing trees are generally more durable than the rapidly growing individuals. In fact, those grown in forests in poor soil at high altitude or upon hill tops are generally more dense in wood, are straighter of body, and have a greater taper.

The summer wood (that which grows in summer) is that strong and lasting part of a tree trunk indicated by the dark rings. The more of this a hard wood contains, the better it is. Hence it should be of rapid summer growth.

Cedar and chestnut and the pines are apt to give good looking poles. Some others (as catalpa) naturally branch to such an extent that they give crooked and knotty poles.

The cost of poles, their maintenance in proper condition, etc., is a large item of expense. It is constantly becoming greater as the timber supply decreases. It is, therefore, more and more important every day to lessen the rapidity of deterioration of this element of the transmission line.

The life of a pole is determined by the rapidity with which "rot" attacks it and the weakest point in warding off this destroyer is at the ground line. The effect is well indicated by Fig. 32. The development of bacteria and fungi from their spores is the cause of the destruction of the wood. These spores are not always deposited in the tree after its felling, but are frequently already at work in the heartwood of the growing tree. For the growth of these destroyers there are required heat, air, and moisture. This shows why the pole is most easily attacked as shown in the figure. It also indicates the method to be used in avoiding the attack, for if any one of these requirements is absent, the mere presence of the woody food is no inducement.

The simplest method of preventing decay and one always practised is the seasoning of the wood. This is done by stripping it of its bark and allowing it to dry in a protected place. The sapwood contains more moisture than the heartwood and also dries faster, due partly to the presence of gums in the latter. Thorough seasoning requires from three to twelve months or

more depending upon the size of the timber, the season of its cutting, the climate, etc. It must be piled so as to admit of free circulation of air between logs.

Winter cutting of poles has been the established custom because of the fact that logs may be handled more cheaply in that season. From the standpoint of seasoning, winter is a little better season than spring for felling. The wood seasons more regularly and more slowly, hence with less checking.

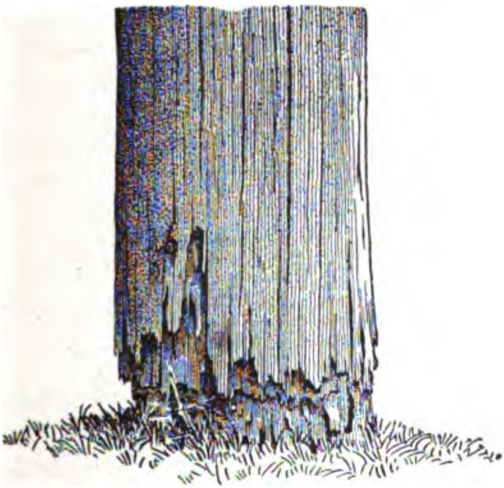


FIG. 32.—Chestnut pole 6 years service.

Spring-felled timber is lighter than winter-felled, but the latter by longer seasoning will be reduced to practically the same weight as the former. In handling these poles, they may be seriously injured by dragging for long distances. The attendant abrasion of the pole surface opens the wood for later absorption of moisture and destroying agencies.

Seasoning under running water seemingly does not partake of the nature of air seasoning. The action is that of solution and washing away of the organic substances supplying food to the fungi. A subsequent air drying will finish this process, which is much shorter than the ordinary one and very effective.

Dry, well-seasoned wood has about twice the strength of green, wet timber.

Preservatives.—The presence of a fungicide in the wood will effectively increase the life of the timber. The spores must enter the wood. They are not inherently found there. Consequently if the entire surface is protected the pole is immune from outside attacks. The weaknesses of this superficial method are several. The spores may have entered the growing tree and begun to develop in the heartwood before it was cut. The surface of the pole may be injured by pole climbers, etc. and then the protecting shell is opened. The result is that this method is generally without much effect.

The deeper the preservative enters the more good it will do. The methods employed for impregnating the poles depend upon the chemical used. Creosote, zinc chlorid, bichlorid of mercury, and copper sulphate are used in the United States. The first two of these are the most common. Creosote is a distillate from the tarry by-product of gas plants and coke ovens. It is very complex, chemically. It is often referred to as the dead oil of coal tar. Poles treated with it are hard to handle and repulsive and must be protected when used in streets or other public places. Zinc chlorid is, of course, a simple compound. It is used in a dilute form.

The Bethell process with creosote and the Burnettizing process with zinc chlorid are one and the same in principle. It is a pressure process. The timber is drawn from trucks into large cylinders. These are sealed and live steam is admitted until a pressure of about 20 pounds is reached. This is maintained for several hours, i. e., until it has penetrated the wood to a proper depth. Pressure is then removed and vacuum pumps are used to exhaust the air from the wood. After several hours the creosote or zinc chlorid is pumped into the cylinders and pressure again applied. If penetration is complete in a well-seasoned pole the amount of creosote used varies from 20 to 25 pounds per cubic foot of wood. Zinc chlorid requires 20 to 35 pounds.

There is also the open tank method of treatment. This consists simply of immersing the seasoned poles in an open tank of hot preservative. Twenty-four hours in such a tank will give a penetration of 4 or 5 inches in seasoned loblolly pine. Heartwood is less easy to penetrate. Seasoning makes a great deal of difference in this process as may be seen by referring to Fig. 33.

The cost of this method of treatment is about 11 cents per cubic foot. Chestnut poles absorb only from 18 to 27 pounds per pole with penetration of 1 inch or less at a cost of less than 70 cents per pole.

The brush method is, as its name implies, simply the process of painting the pole thickly with hot preservative. This is not

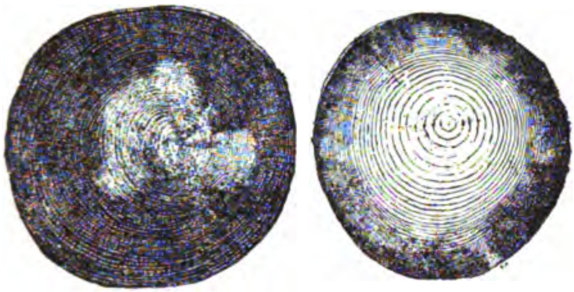


FIG. 33.—Penetration of preservative in seasoned and unseasoned loblolly pine.

easily done in winter. From one to three coats are applied. Special attention is usually paid to that portion of the pole which will be at the surface of the ground, namely, about 3 to 8 feet from the butt. A penetration of a quarter of an inch may be

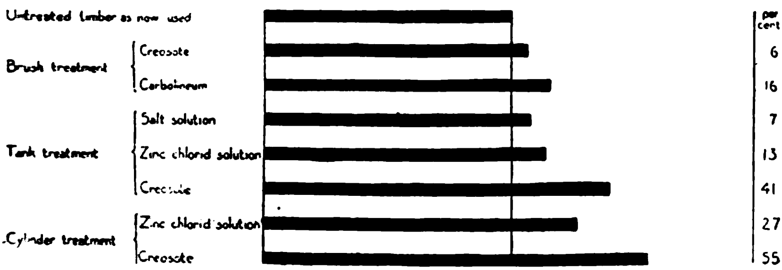


FIG. 34.—Increased life necessary to pay cost of preservative treatment.

reached in chestnut and cedar. This is accomplished with creosote at an average cost of about 30 cents per pole.

Figure 34 shows the approximate increase in life necessary to pay for the treatment of poles by different methods as practised by the United States Department of Agriculture. In the case of pressure treatment with creosote the estimate of increase of life

is 150 per cent. as compared with a necessary 55 per cent., all above which is pure gain. The open tank treatment will certainly increase the life of the pole at least 100 per cent. as compared to the 41 per cent. needed. The brush process will give 25 per cent. as against a 6 per cent. added expense. These estimates of increase in service life are, of course, not citations of actual cases because the matter has not been studied in this country for a sufficiently long time to give recorded results. There are cases, however, of poles in service 20 to 30 years or more and still showing no indications of weakness.

A still farther saving could be made by a process to thoroughly treat the butts only, as in many localities this is all that is needed.

Probably one of the most important features of the growth of the custom of treatment is that it will allow the economical use of cheap but inferior woods, trees not now used because of their very quick decay.

It has recently been found that a live tree may be made to fill its own body with certain preservatives. This process has not been studied sufficiently to become of commercial importance, although it may later affect the cost of the operation.

Of the other preservatives mentioned, $HgCl_2$ is used in the "kyanizing" process, steeping the pole in a weak solution. Its use is rather restricted. The $CuSO_4$ is hardly ever used any more.

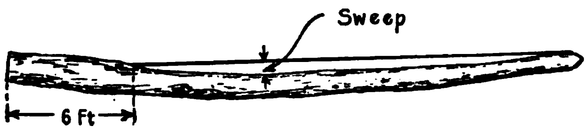


FIG. 35.—Measurement of pole sweep.

In none of the processes should very high temperatures be used as this will injure the timber. Charring the butts of untreated poles is effective to a fair degree.

Specifications for poles should cover the sizes, lengths, top diameter, butt diameter, straightness, defects, etc. The Table XVI shows good values of dimensions from which approximate figures may be selected.

It is usually stated that all poles are to be cut from live timber, are to be peeled, trimmed, and squared at each end. A 1-inch

sweep per 5 feet is the maximum allowed. Sweep is defined as the displacement of a pole surface from a straight cord stretched from the pole top to the pole base. In making this test that part of the pole to be set in earth is not considered. (Figure 35 will illustrate this process.) This deflection is to be in one direction only, i. e., no double crooks are allowed. Butt rot exceeding 10 per cent. of butt area is a defect as it is assumed that this will extend into the body far enough to weaken it. Sound knots are not considered as defects. Wind twist is not necessarily a defect. These specifications apply to the poles as purchased in large quantities, and do not indicate complete specifications for poles ready to set. The latter must be prepared for cross-arms, pointed at the top, or "roofed" as it is called, etc.

Table XVI.—Pole Dimensions.

The following proportions are recommended for cedar, chestnut and juniper pole dimensions.

	Cedar.				Juniper.				White chestnut.			
Length in feet.	Cir. at top.	Cir. 6 ft. from base.	Cir. at top.	Cir. 6 ft. from base.	Cir. at top.	Cir. 6 ft. from base.	Cir. at top.	Cir. 6 ft. from base.	Cir. at top.	Cir. 6 ft. from base.	Cir. at top.	Cir 6 ft. from base.
Ft.	In.	In.	In.	In.	In.	In.	In.	In.	In.	In.	In.	In.
25	22	31	25	34	22	28	25	33	22	27	25	30
30	22	34	25	36	22	33	25	35	22	30	25	34
35	22	38	25	38	22	35	25	40	22	34	25	37
40	22	42	25	43	22	40	25	44	22	37	25	42
45	22	44	25	47	22	45	25	48	22	42	25	46
50	22	48	25	50	22	47	25	51	22	46	25	48
55	22	53	25	55	22	50	25	53	22	49	25	50
60	22	57	25	61	22	56	25	57	22	51	25	54
65	22	63	25	66	22	63	25	63	22	55	25	58

Cross-arms for wooden poles are also of wood. Yellow pine, Oregon fir, cypress, cedar, etc., are used. It is necessary that they shall be absolutely sound, straight grained, free from knots, and thoroughly seasoned. Three and a quarter by four and a quarter inches is considered good practice for the sectional dimensions of arms for ordinary light work. Many lines for very light work, where few telephone or telegraph lines are strung, are fitted with lighter arms than the above. The lengths are always dependent upon the number of pins to be borne or the voltage of power lines. Necessarily, as lengths increase so also must cross-section, partly due to increased strains and partly due to increased size of holes for the pins. Standards have not been established but heavy lines use such sections as 4 x 5 inches, 5 x 6 inches, 6 x 7 inches, and intervening values. For tables of sizes, etc., see Chapter IV.

The upper edges of the arm should be beveled. This leaves less flat top for retention of moisture, still leaving a flat seat for the pin. The rounded top is not advised because the shoulder of the pin finds no even bearing surface.

Cross-arms have a shorter life than do poles. They are always sawed and this leaves open grain for the absorption of moisture. The position and shape of the arm is not one conducive to rapid drainage of rain from the surface. It is small in section compared to the pole and hence presents a greater percentage of surface for deterioration. These reasons for decay necessitate especial care in selection of cross-arms as above noted.

They should be at least painted, though it is preferable to have them treated with some preservative. This may be similar to that used with poles or it may be linseed oil in which the previously well-seasoned arm is boiled until thoroughly impregnated. Special attention should be paid to the preliminary seasoning whatever the subsequent treatment. It is well, if possible, to keep cross-arms upon hand for several months after delivery, stored in a dry, well-protected place. In case this can be done they may be ordered unpainted as follows:

"Cross-arms shall be cut from sound, well-seasoned, straight and close-grained timber, planed upon all sides, beveled and bored as required. They shall be free from sap, knots, splits, and

other defects, and shall be delivered unpainted. (Dimensions and kind of wood also inserted.)"

Pins.—When the insulators are mounted upon pins, the latter may be of wood or metal. Wood is used for all telephone and telegraph lines and for low-voltage circuits. Medium and high-voltage power lines are better suited by metal pins.

Wooden pins are of locust, oak, eucalyptus, or hickory. The grain must be straight and fine and without knots. They are made with a shank which fits into a hole bored into the arm and a shoulder which rests upon the top of the arm. From the shoulder upward they may decrease in size until of sufficient height for the insulator to be used and then are straight topped with coarse threads. They may be secured plain, painted, or paraffined.

While no standards are established, Mr. Ralph D. Mershon has proposed that such steps may be taken and suggests the following specifications in a paper before A. I. E. E., Vol. XXI.

"*Threaded End.*—It is proposed to make the diameter of the small end of the pin 1 inch; the length of the threaded portion 2.5 inches; and the diameter at the lower end of the threaded portion 1.25 inches, so that the threaded portion will taper from 1.25 inches to 1 inch in a length of 2.5 inches. The threaded portion of the insulator should have the same dimensions and taper as that of the pin.

"*Shoulder.*—It is proposed to make the shoulder 3/16 inch on all pins. That is, the diameter of the pin just above the cross-arm will be 3/8 inch greater than the nominal diameter of that portion of the pin in the cross-arm; it is proposed to carry this diameter 1/4 inch above the cross-arm before tapering the pin.

"*Dimensions in Cross-arm.*—It is proposed to make the dimensions of that portion of the pin in the cross-arm just below the shoulder 1/32 inch less than the diameter of the hole in the cross-arm and at the lower end of the pin 1/16 inch less than the diameter of the hole in the cross-arm. It is proposed, also, to designate this portion of the pin as having a nominal diameter equal to that of the hole in the cross-arm into which the pin fits. Therefore, that portion of a pin which is to fit a 1 1/2 inch hole in a cross-arm will have a nominal diameter of 1 1/2 inch, but

will have an actual diameter just below the shoulder of 1 15/32 inches, and at the lower end of the pin of 1 7/16 inches.

"*Thread.*—It is proposed to use on all pins a thread having a pitch of 1/4 inch or 4 threads to the inch. * * * The angle between the faces of the thread is 90 degrees and the top of the thread is flattened by cutting off, from the form the thread would have if not flattened, one-fourth its unflattened depth. The form of the thread in the insulator should be the same as that on the pin. If this is done it will insure the bearing surface's being always on the sides of the threads and never on the edges.

"*Designation.*—It is proposed to designate that portion of the pin above the cross-arm as the "stem" of the pin; that portion in the cross-arm as the "shank" of the pin. It is proposed to

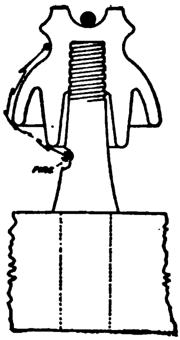


FIG. 36.—Discharge or arc path, wooden pin.

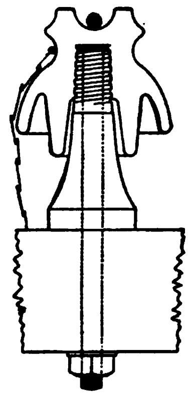


FIG. 37.—Discharge or arc path, porcelain base.

designate a pin by the length of its stem, i. e., a pin whose stem is 5 inches long will be designated as a "5"-inch pin, one 6 inches long as a "6"-inch pin, etc."

Wooden pins with center bolts for fastening are of frequent use. They are better described as metal pins with wooden tops, as the steel bolt furnishes the strength of the pin, the wooden top serving in mounting the insulator. The metal parts are preferably galvanized and the pin paraffined. These steel pins may be furnished with porcelain base instead of the wood. They are more durable when thus assembled and increase the insulating

value of the support by lengthening the rupture path to the wet wood. (See Figs. 36 and 37.) One advantage that these pins have over the plain wooden pins is that they do not need so large a hole in the cross-arm and therefore do not weaken it so much. Metal pins are of various shapes. They may be of galvanized iron or steel, either one piece or a base separable from the shank bolt.

Economy requires that when an insulator is broken the pin may be used again. This is accomplished by providing a separable top to the pin or by supplying the insulator with a thimble

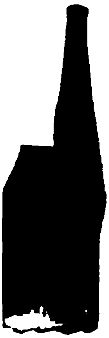


Fig. 38. One-piece metal pole top pin.

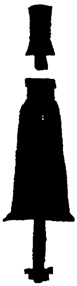


Fig. 39. Separable top metal cross-arm pin.

Fig. 40. One-piece pipe pole top pin.

Fig. 41. Separable top pipe cross-arm pin.

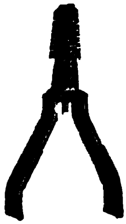


Fig. 42. Ridge iron and pin.

fitting the metal pin. Frequently, however, the insulators are cemented directly in place upon solid pins. In the latter case, the fastening cannot be done at the factory but must be done out on the line. Various pins are illustrated in Figs. 38 to 41. Figure 42 shows a special pin mounted upon a *ridge-iron*. It may be used on a pole top.

One further type of pin is required for regular work—that used with the strain insulator for dead-ending a line, etc. As this pin is supported at both ends (i. e., it goes through the insulator and extends into the cross-arm above and cross-arm below), it is made of split hickory, paraffined, wrought iron pipe, or cold rolled steel according to the demand made upon it. It varies in length from 15 to 25 inches and in diameter from 1 1/2 to 2 inches. When metal is used a flexible fiber sleeve is placed between the metal and the porcelain.

Concrete Poles.—The fact that reinforced concrete is both strong and durable has led to its use in a rather limited way in the construction of poles. Of its decided advantages we note

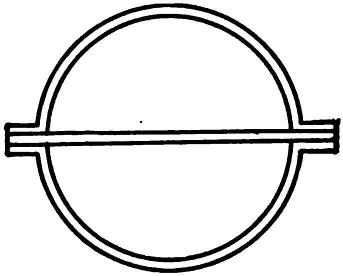


FIG. 43.—Section of tubular steel pole.

FIG. 44.—Steel lattice pole, New York Central and Hudson River Railroad.

that it may be made directly upon the ground. It may be designed for its particular position in the line and may be long, short, or even approximate a pier, as upon a river brink, etc. Instead of deteriorating with age, it will become stronger. It

is, however, an expensive construction compared to wooden poles but is, perhaps, less expensive than steel poles.

Under a continued strain in one direction these poles are apt to take on a permanent set.

The Lincoln Electric Light and Power Company on the Welland Canal have used such construction for two poles reaching the

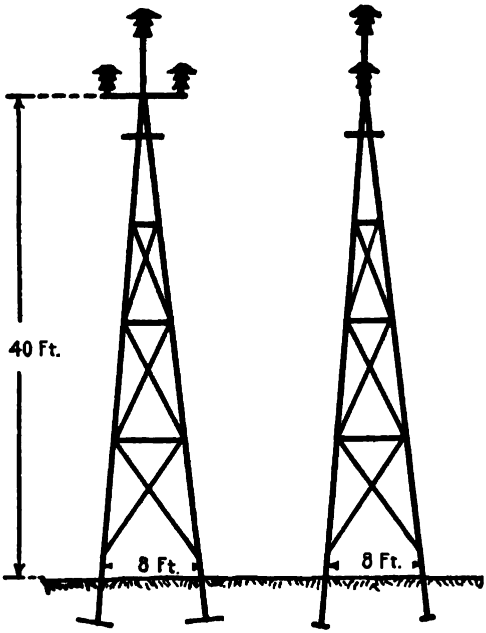


FIG. 45.—Steel tower, one circuit.

height of 150 feet. They measure 31 x 31 inches at the base and 11 x 11 inches at the top. They are set 16 feet in special concrete bases in earth. The reinforcement used is a set of steel rods. The mixture used for their construction was 1 : 2 : 4 (cement, sand, broken stone).

The weights of such poles are excessive, being some 5 tons for a 50-foot pole. Such weights can be handled only by derricks.

Iron poles.—When it is desired to use a more solid construction or a more ornamental one, the use of iron poles may be considered.

These are to be found in a great variety of forms. One consists of a pole built up of successive lengths of iron pipe shrunk upon each other. This gives a round pole with diameters decreasing toward the top in steps of about 1 inch. There are generally three or four sizes of pipe used in one pole, with 6- to 10-inch base. The lowest section is the longest one, as some 5 or 6 feet

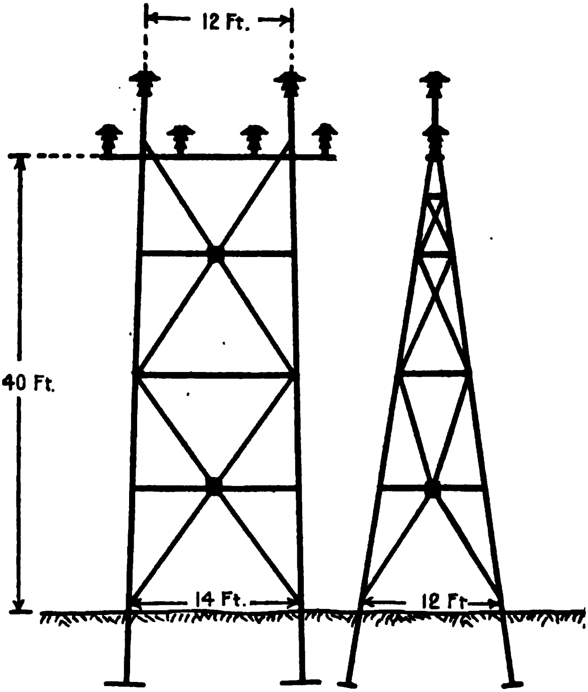


FIG. 46.—Steel tower, two circuits.

of it will be set below ground. A special top is provided to complete the design from an ornamental standpoint and at the same time close the pole to avoid internal rusting. Special rings or collars at each joint also add to the decorative effects and serve to protect them. Inspectors should note before purchasing that joints are solid and present sufficient binding surface. These poles are generally used in shorter lengths only, such as

for railway work, etc. If cross-arms are used, they are of the same material and are bracketed with ornamental scrolls.

Another form of built-up pole is the tubular pole consisting of two sheet-steel hollow columns, each of semicircular cross-section placed face to face with an intervening web and riveted together. The flanges for riveting, etc., are shown in the sectional view of Fig. 43. Latticed poles make a good design, neat in appearance, and should be serviceable. They have been adopted by the New

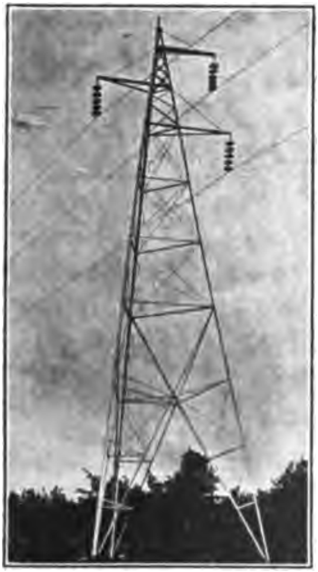


FIG. 47.—Grand Rapids and Muskegon three-legged tower.

York Central and Hudson River Railroad in their electric zone in New York City. Such a pole is illustrated in Fig. 44, taken from a paper in the Trans. A. I. E. E., 1907, by F. J. Sprague.

Steel Towers.—Much of the heavy power transmission of to-day requires special and exceedingly sturdy construction. The poles heretofore discussed are not of sufficient ruggedness to cope with the strains. Even when wooden poles are grouped, they fall short of the demands often made upon them. A corresponding

enlargement upon the idea of the steel poles leads to the tower construction. This may be of any degree of massiveness, from that which easily might be replaced by a wooden tower to those of extreme weight, height, and strength required for spans 1/2 mile long. They may be designed for one circuit or for more.

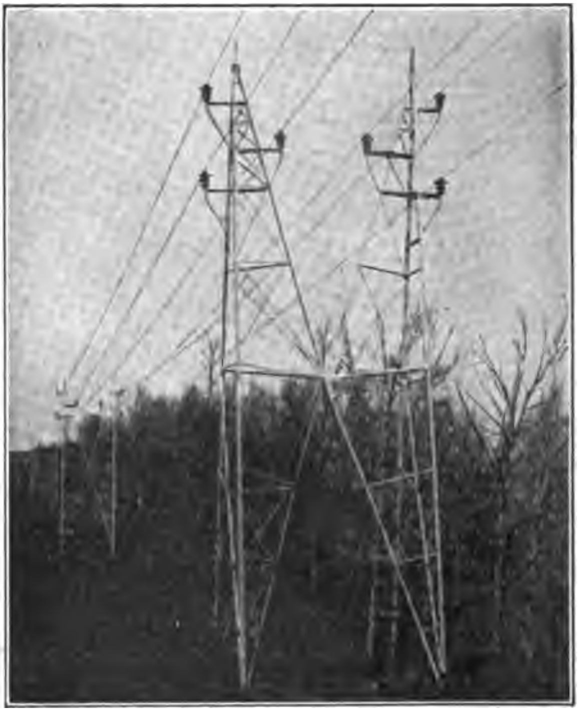


FIG. 48.—Southern Power Co. double aermotor towers.

The simplest form is the natural outgrowth of the latticed pole, above referred to. It is the *windmill tower type*, is built of structural steel, and has four legs interbraced and fastened together at the top. The spread of the legs is approximately one quarter the height of the tower. Any horizontal section is a square. The pole is designed for one circuit. A simple divergence from this construction will permit the support of two circuits. It consists in bringing the legs, not to a point but to a

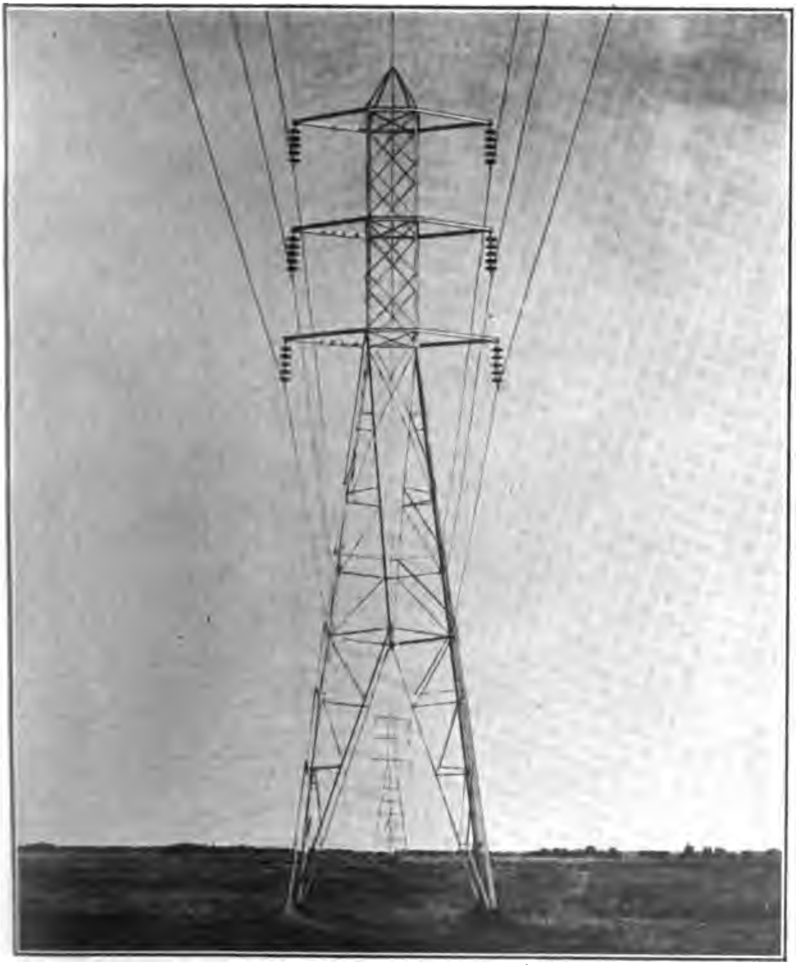


FIG. 49.—Double circuit, Milliken Tower Line, Great Western Power Co.

ridge where the ridge pole is the cross-arm for the lower insulators and the posts are extended to two points for the upper insulators. These two types are shown in Figs. 45 and 46, respectively.

The three-legged type of tower shown in Fig. 47 is built by the Aermotor Company, having originally been developed for windmill towers. This particular illustration is of the 110,000-volt line of the Grand Rapids and Muskegon Power Company in Michigan. Suspension insulators are used, although, as far as

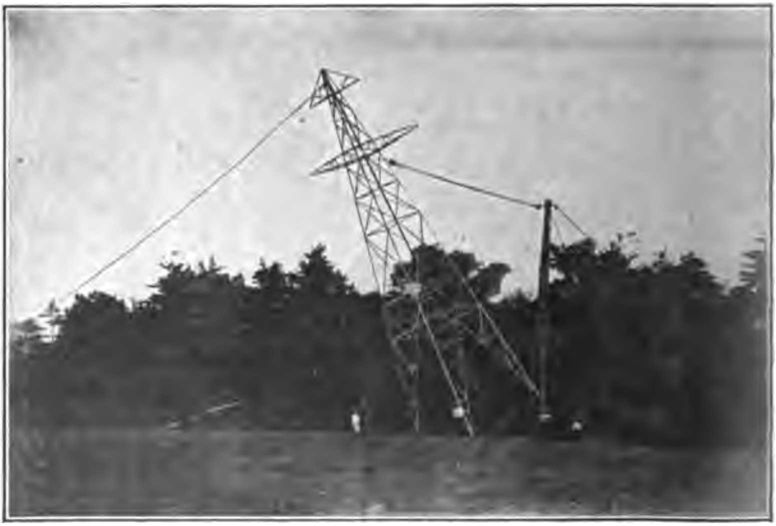


Fig. 50.—Hydro-electric Power Co., Ontario.

the tower is concerned, the pin type of insulators is equally usable. Figure 48 shows the combination of two such aermotor towers for a two-circuit line. The union gives a four-footed tower. The pin insulator is used in this case, which shows the line of the Southern Power Company, transmitting at 60,000 volts.

The Milliken tower (Fig. 49) is one very frequently seen also. With it, the equilateral arrangement of conductors is abandoned and a vertical plane adopted instead. Two circuits are carried and the whole is capped by a ground wire at the peak of the tower.

One of the recent lines built to retain the equilateral spacing of wires is that of the Hydro-electric Power Commission of Ontario. A four-footed tower is used (Fig. 50) with two steel cross-arms.

FIG. 51.—Rochester and Sodus Bay, A-type flexible tower.

Among the most recent developments of steel towers are the flexible towers. These are built with two legs, set crosswise of the direction of the line, allowing some yielding along the line. It may be either the A-type or the H-type (Figs. 51 and 52). When suspension insulators are used with this tower it becomes almost necessary to use a sliding sleeve clamp upon the conductor.

This is to avoid the pull of the conductors upon the towers themselves. With pin insulators this would also be preferable, especially for spans of any considerable length. Without such precautions, the breaking of the conductors at any point would cause an unbalancing of strain and might pull down tower after tower in each direction from the break. When the open

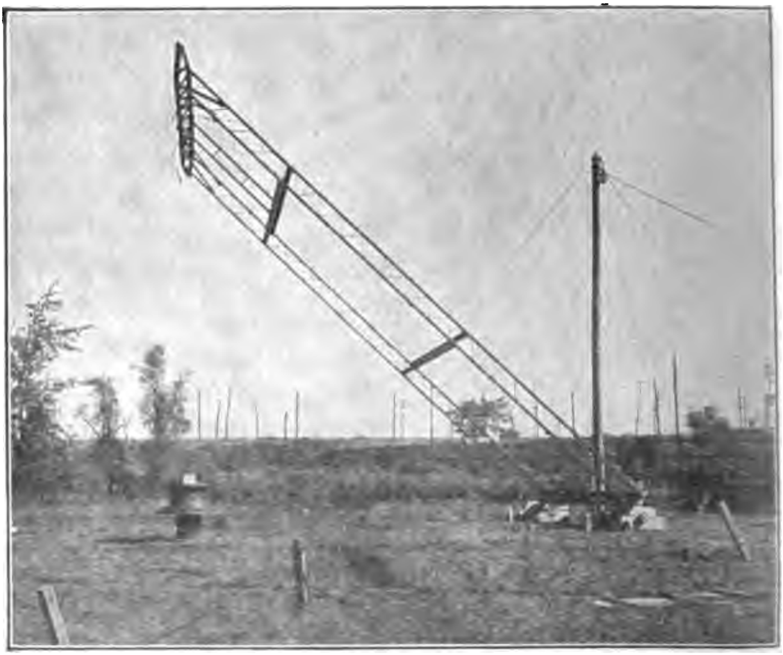


FIG. 52.—General Electric experimental circuit, H-type flexible tower.

sleeve support is used, the conductor merely slides through the clamp and spans sag more and more till the pull is relieved.

Figure 53 shows an exceptionally large and heavy tower constructed at the bank of the San Joaquin River upon the line of the Great Western Power Company. The river span is about 3000 feet in length and demands very sturdy towers of considerable altitude. Such towers as these are always special and should be built for the individual settings and loads they are to receive.

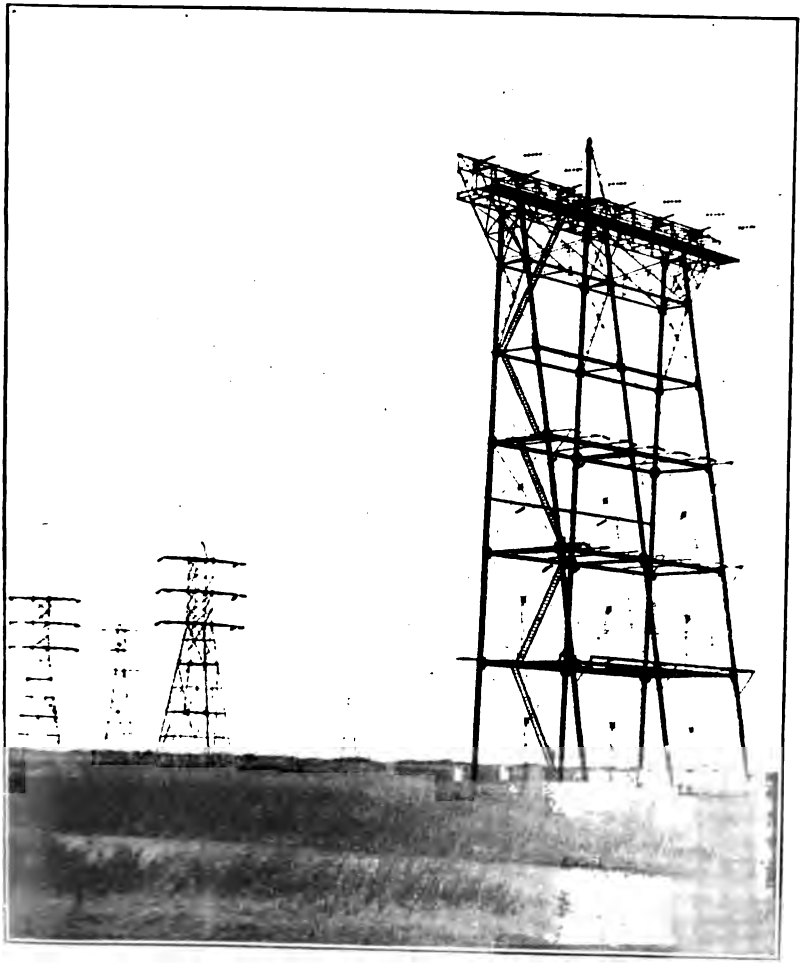


FIG. 53.—Tower of Great Western Power Co., 3000-foot span at the San Joaquin River.

CHAPTER IV.

AERIAL LINE CONSTRUCTION.

Right of Way.—It is neither necessary nor customary for a company to purchase a right of way except for special reasons. The transmission line will be constructed without actually occupying a great deal of room or greatly restricting the use of the land for some other purposes. Trees, shrubbery, etc. must be kept cleared away and at least a passable path provided for the line inspector or patrolman.

When the region is wooded, a definite width is thus cleared. This width depends upon two things, the height of the trees and the height of the pole line or lines. Storms will often throw down dead trees or uproot live ones which, in falling, may strike their tops into the live wires or even crush down a pole. Hence, the clearing should extend to each side of the line to a distance exceeding the average tree heights. Pine forests, etc., may cause trouble in time of forest fires, but this is so uncertain a factor that it is hard to guard against by widening the clearing. If two lines are to be run, they should be separated far enough so that one, if blown down, cannot strike the other. This necessitates the determination of the three distances, two equal outside or marginal clearances and the inter-line distance.

In open country the distance between two parallel lines should be determined as above. The outside spaces need not be of any particular uniform width but will depend somewhat upon the voltage of the line. It is good practice to run telephone lines along public highways, which means with practically no reservation of land. This gives an easily accessible route for construction, inspection, and maintenance. It is not good practice to run power lines through the same kind of thoroughfares, especially if voltages are above 2300 volts. The reason is two-fold. The line is subject to the mischievous attacks of passersby, from the boy who throws a wire over the lines to the sportsman who

takes a pot-shot at the insulators. And a line once injured in this way or by storms is in dangerous proximity to a careless public, ignorant of the principles of self-protection when it comes to electric shocks. Wherever right of way is secured, it is necessary to reserve also the right to establish convenient entrances to enclosed areas across which the line passes and to permit perpetual attention by inspectors and repairmen.

The line must be surveyed and staked. This is advisable even with the simplest lines as it assures alignment, uniformity of spacing, and hence of sag, strains, etc. Where the construction is heavy, it is absolutely necessary to make this preliminary determination. In fact, the record should be made not only of the location of line, its angles and lengths, but also its profile, elevations, etc. Then, the design may be made to include the assignment of pole heights to definite localities.

The route must be studied from the geological standpoint also. For this will determine depths of setting poles or towers, as well as other details of method. It will also fix the exact location of poles in many instances allowing for guying, for proper foundation, etc. A meteorological survey is always advisable, as will be shown in the discussion of Right of Way in Chapter X.

The design and construction of a transmission line are matters depending wholly upon the individual characteristics of the project considered. Each proposal has a mass of conditions attached to it unlike any other line in existence, and details must be planned to meet the particular requirements we may have before us. The failure of mere minutia is the failure of the whole. If one link breaks, the chain ceases to hold. Here it is especially of importance that no defection may occur, for when such an event does take place we cannot presage where it may stop. The loosing of electric power from the bounds set for it is oftentimes liable to the most sudden and destructive consequences. This may mean the endangering of human life, it may mean only the devastation of property; but even the lesser of these calamities is great enough to defeat the purpose of the enterprise.

The fundamental principle may, then, be enunciated that it is never permissible to build in such a way that ordinary operation will be carried on with undue risk to human life. Nor is it to

be considered profitable to restrict safeguards to property to such an extent that troubles are frequent and serious.

Certain types of lines have these characteristics much more prominently than others. For example, the telegraph line and the telephone line are not in the same class as the railway line, while the latter is not comparable to the high-voltage power transmission line. Aerial lines and underground lines have quite different features. Moreover, the general features of construction of aerial lines and of underground lines are so dissimilar that they will be considered separately, the latter being reserved for the next chapter.

When wooden poles are used there should be borne in mind the characteristics already discussed in reference to the kinds of wood, cutting, seasoning, defects, preservative treatment, etc. Specifications should be very carefully drawn to cover all the requirements. Ordinarily, the poles may come all ready prepared for assembling the cross-arms by having the 1/2-inch gains cut in their tops as needed.

In choosing dimensions for poles, the height and the weight of conductors or number of wires supported are the determining features. In no place should the center of the span of wire sag to less than a height of 20 feet above the ground. Sufficient clearance should be provided for other cross lines, etc.

In telephone practice, Kempster B. Miller tabulates for 7-inch tops the heights and base diameters as in Table XVI, Chapter III. It is not universal practice to use poles of these diameters, but they indicate normal telephone practice. Where the number of wires carried is large, much sturdier construction is advised, as also in the case of corner poles, those on curves, end poles of a line, etc. These general sizes correspond to ordinary city practice with about 20 to 30 wires. For heavy city work of more wires than this, poles of 8-inch tops or larger are preferred, while 5- or 6-inch tops may be used upon light suburban lines or country roads. Before shipment is made, weights of poles of different lengths and diameters should be obtained from the dealers in order that consignments may be adjusted for economical shipment by combining different sizes in the same lot. For short and medium-length poles, single cars up to 40 feet in length may be used to carry about 30,000 pounds.

For long poles double cars are required and a correspondingly large load may be ordered to advantage. If many poles are required, as for a long line, they may, by preliminary planning, be shipped to different points along the line and thus avoid excessive haulage. This might mean carloads of quite heterogeneous sizes as successive poles in a line are not necessarily of the same height. In fact, in order to avoid too rapid and excessive changes of level, shorter poles are generally used on hilltops

FIG. 54.—Ice storm of unusual severity.

and longer poles in the hollows. Similarly, long poles will be needed at points of crossing of railroads, other transmission lines, etc. Frequently, city lines are carried above lighting or railway circuits in all streets, and in one instance at least, they are carried above the tops of shade trees which are kept trimmed down to avoid interference. These emergencies demand 50- to 60-foot poles.

Spacing of poles will be determined by weight of pole used, number of wires carried, liability to sleet and ice storms or to

high winds. Damage done by storms is unexpected in some localities but of frequent occurrence in others. The North Atlantic coast is peculiarly subject to this danger and the results are occasionally very disastrous. Figure 54 illustrates some of the results of a heavy sleet storm which occurred February, 1909. The photograph was taken in Ohio.

It is impossible to escape injury from such a storm by any current economical aerial construction. Underground construction will protect the lines, but at an increased expense and a decreased accessibility. It would, however, be out of the question to space poles, for instance, so that a severe ice storm due perhaps once in 8 or 10 years, would not damage the lines. Thirty poles to the mile (about 175 feet apart) is a minimum permissible number and is poor practice. Forty poles per mile is better and is considered good practice. Fifty poles, or with spacings of about 100 feet, is much to be preferred, especially if the line is installed where the number of conductors carried is liable to increase. And where heavy work is to be installed at once, the number of poles per mile may still further be increased. Careful spacing near corners will frequently permit double-pole corners, which are much to be preferred.

Poles are set in earth to a depth of from one-eighth to one-fifth of their lengths, for tall and short poles respectively. For example, a 25-foot pole should be set about 5 feet, a 75-foot pole about 9 1/2 feet. The 150-foot cement poles mentioned in Chapter III are set 16 feet in earth and have large concrete bases. If the pole is set in solid rock, perhaps two-thirds as deep is sufficient. Where ground is wet or marshy and will not hold firmly a greater depth is necessary (or some special setting). Table XVII taken from Matthews' Telephone Line Construction Book indicates good practice in this respect. The holes may be dug or bored as preferred. They should be about 1 foot larger in diameter than the pole base and full size to the bottom, in order to allow for proper tamping of the earth around the pole, as well as ease of placing.

Augurs are seldom serviceable because of the lack of favorable soil, and because of the large diameters of holes. They must also be of extra length. When augurs are used the hole will be of uniform width and of smooth sides and will perhaps be slightly

less liable to crumble in inserting the pole. In digging the holes, sturdy long-handled sharp-nosed shovels are needed, with a decided bend at the neck. For the final work of removing the earth loosened by the digging shovel, a *spoon shovel* is used (Fig. 55).

Table XVII.—Depth in Feet of Holes for Setting Poles.

Line (height).	Solid ground.		Soft ground.		Solid rock.
	Poles (depth).	Corners.	Line.	Corners.	
22	5.0	5.0	5.0	5.0	4.0
25	5.0	5.5	5.5	6.0	4.0
30	5.0	5.5	6.0	6.5	4.5
35	6.0	6.5	6.5	7.0	4.5
40	6.5	7.0	7.0	7.5	5.0
45	6.5	7.0	7.0	7.5	5.5
50	7.0	7.5	7.5	8.0	6.0
55	7.5	8.0	8.0	8.5	6.0
60	8.0	8.5	8.5	9.0	6.5
65	8.5	9.0	9.0	9.5	6.5
70	9.0	9.5	9.5	10.0	6.5
75	9.5	10.0	10.0	10.5	6.5
80	10.0	11.0	11.0	11.5	7.0
85	10.5	11.0			
90	11.0	11.5			
95	11.5	12.0			
100	12.0	12.5			

Guy stubs should be set not less than 7 feet in any soil except solid rock.

It is probable that the earth, especially in stony ground, will need to be loosened by what is known as a *digging bar*, a long

Fig. 55.—Construction tools.

straight iron bar with a wide chisel end (Fig. 56). In rocky soil or in solid stone, dynamite must be used.

The poles having been distributed by throwing from a car,

or by hauling (never drag a pole any great distance) they will lie with butts in the immediate neighborhood of the holes. Hickory-handled *cant-hooks* are used in rolling the pole about (Fig. 57) and adjust themselves to the diameter of the poles. Where it is

FIG. 56.—Construction tools.

necessary to carry the poles at all, it is advisable to use special devices for hauling them unless they are the very smallest sizes.

A *carrying hook* is shown in Fig. 58. They may be had with handles 4 feet to 7 long. A pole will be rolled or carried to rest

FIG. 57.—Construction tools.

FIG. 58.—Construction tools.

with butt above the hole. A board should be provided for the butt to bear upon while the pole is being raised. This will avoid the crumbling of the earth as the pole is being lowered into the hole. There seems to be an opportunity for the development of

FIG. 59.—Construction tools.

some simple socket for the pole to rest in while being raised, no successful device of this sort being in use to any extent. The pole is generally raised by man force. Gangs of ten to eighteen men are employed depending upon sizes of poles, etc. A 30-

FIG. 60.—Construction tools.

foot pole can be raised by seven or eight men. The tools used will include several lengths of *pike poles*, 10 to 18 feet, or of *raising forks* of about the same lengths (Figs. 59 and 60). The handles are of 1 3/4 to 2 1/4 inches in diameter. These are used,

one tool per man, in the actual raising of the pole, first using the shorter lengths and then the longer ones, in order to keep as far up the pole as possible. Pole supports serve to take the weight of the pole during a halt in the process if they are placed under it and kept closely adjusted. They may be single-legged *deadmen* (Fig. 61) or the cross-legged *jenney*. These, of course, are only 6 to 8 or 10 feet long.

It is much simpler and easier to put on the cross-arms before the pole is raised and this gives the workmen the means of accurately adjusting the pole by cant-hooks to its proper position before they tamp in the earth, as they can place the arm at right

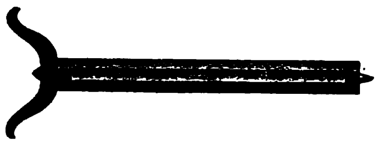


FIG. 61.—Construction tools.

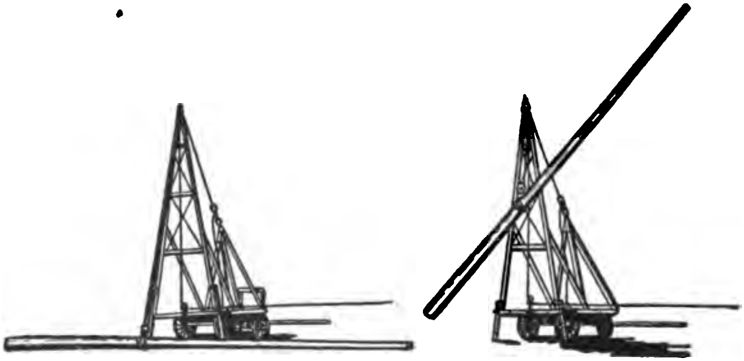
angles to the line. When, for any reason, it is preferable to leave the arm to be placed after the pole is set, it is desirable to nail a light board in the pole gain, letting it extend some 4 feet or more from the pole. If nailed at the end of the board rather than at its middle the same length board (a lath) will more easily indicate inaccuracy in adjustment. The cross-arms must be finally at right angles to the line, hence the necessity of this care in pole-setting.

When the pole is up and arranged, the earth must be firmly tamped as it is shoveled about the base. It should not be necessary to haul away any earth. It is not too much to require four tampers to one shoveler. Time saved in tamping in the earth is multiplied by large factors and lost in keeping poles erect.

The use of some form of pole-erecting derrick so constructed as to be quickly and easily adjusted is especially to be commended. There are several more or less capable affairs of this kind, some being intended to handle light work only, others designed for the heaviest poles ever used. When it comes to a tall pole, such practice is necessary, because it is impossible to use pike poles below the center of gravity of a pole till its butt has entered the

hole and is bearing heavily against the side earth. A good form of derrick is one in which there is a platform swung below the sturdy axles of a wagon and supporting a hinged boom of adjustable length. The pole is swung by block and tackle from the end of the boom, and the boom itself is supported and its position regulated by rope and pulleys to the front end of the platform.

Another type, known as the "Polerector" (Figs. 62 and 63), differs from the above in some features. The wagon platform is above the axles and the boom consists of two timbers interbraced. W. N. Matthews & Brother, the manufacturers, say of it, "An average of 40 to 50 poles, any length up to 50 feet, can



FIGS. 62 and 63.—Pole erector or derrick.

be put in their holes with the Polerector by two linemen and a boy to handle the team, in an eight-hour day. The saving effected will be between 35 and 60 per cent., the amount depending upon the length of poles handled. The saving is greater on long poles than on short poles."

These erectors are very useful in removing poles from their holes when they are being taken down for any cause whatever. In this work it is not necessary to dig down to the bottom of the pole, but the last 2 or 3 feet may be left in contact with the pole. The strain is a lifting one and will pull the pole out.

It is very often necessary to place poles in wet or loose soil. Here, if sufficient stability cannot be secured by setting them deeper than usual, it may be best to put in large stones or base plates of two heavy boards fastened at right angles to each other,

across the bottom of the pole. If the soil is marshy, such simple precautions as the above are insufficient and the pole will pull out of alignment. Various devices are resorted to in such cases.

The bottom of the enlarged hole is sometimes filled with a broken-stone concrete mixture 1 : 3 : 5, giving increased area of base. The pole is then set and a filling of concrete put in around it. This increases stability very materially. Where it is not deemed

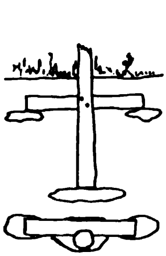


FIG. 64.

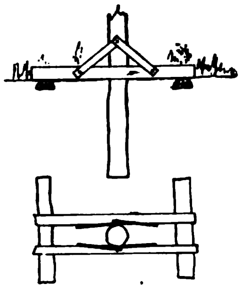


FIG. 65.

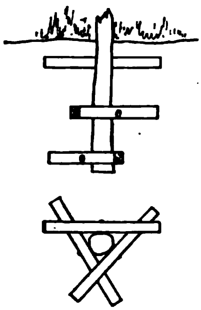


FIG. 66.

FIG. 67.

FIGS. 64 to 67.—Pole-setting in unstable earth.

expedient to go to this expense, a set of timbers bolted crosswise upon the base may be substituted. The timbers should be double bolted or braced to avoid skewing. They should rest upon logs or stones of sufficient size to give a large effective base. Where the cross pieces are placed near the surface of the earth and also near the bottom of the pole they help to maintain the pole erect. Placed at the mid-point of the buried part it does

little good in this respect. It is just as satisfactory as a support from sinking, however. Figures 64 to 67 illustrate some of the schemes suitable for these purposes.

Seldom will such precautions serve to eliminate danger of tipping to one side and, except where positively necessary, it should not be depended upon to fill this office. Where plain setting is sufficient for straight line work as in good solid earth, it may, however, be used for corner poles, curves, etc., in the absence of conditions suitable for guying. In other words, it is much better than nothing, where guying cannot be installed.

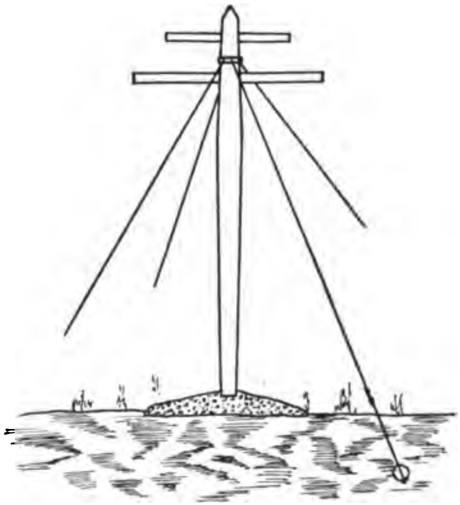


Fig. 68.—Mast pole.

A type of pole-setting that is sometimes serviceable for swampy land may be called the mast pole. A concrete base is built at the surface of the ground large enough to sustain the entire weight of the pole and its load. A suitable seat is prepared in its center for the pole base. The pole is then guyed in order to maintain it in place as the base furnishes no lateral support. This form of setting is illustrated in Fig. 68.

In case of a solid rock foundation, the stone itself may take the place of the concrete in the above design and essentially the same construction may be used.

When poles are set in solid rock, as has already been mentioned, they may be sunk to a depth about two-thirds of that which would obtain in soil. Particular care should be taken to wedge large pieces of rock about the base of the pole to give firmness. Likewise, near the surface there should be the same precautions taken. The smaller rock may be tamped in about the base, although this does not insure a close-fitting mass of stone.

Guying is necessary where changes of direction of the line occur either in angles or curves and also on unavoidable sharp changes of level or at the end of a line. The material used is galvanized iron or steel wire or cable 0.25 to 0.5 inch diameter. Only the lightest strains should be carried by the solid wires and then by use of Nos. 3 or 4 B. & S. gage. The cables should be used for all others and may be used throughout. The galvanizing is tested by dipping samples into a saturated solution of $CuSO_4$ at 60° F. and allowing them to remain 1 minute, when they are withdrawn and wiped clean. This process will be repeated four times, after which there shall be no reddish deposit of metallic copper upon the wire, indicating that the zinc coating is too thin. The zinc must not crack or peel if the wire is bent around a cylindrical bar having a diameter about twelve times that of the wire used.

Many engineers specify that the wire shall be twice dipped in the molten zinc, but if it is properly done, giving time enough for the wire to become thoroughly heated, the first dipping gives as fully a continuous covering as will two baths. A second immersion serves to roughen the surface and leaves more projecting points to be carefully wiped away upon its emerging from the vat. It is of doubtful value.

All clamps should be similarly protected from rust, as should bolts, nuts, guy rods, turn buckles, etc.; in fact, all iron used for this purpose will quickly fail unless it is thus treated. It is useless to install them with the certainty of having to replace them within a year or two and at the same time have the line insecure because of their unreliability.

A new process of preparing line material to keep it from rusting is called "Sherardizing." By the process, there is formed at the surface of the iron or steel an alloy with zinc and then, upon the top of this is a zinc coat. Heating in the presence of vapor-

ized zinc gives these coatings. The product is smooth, easy to handle, and very durable.

The actual guying cannot properly be planned in advance of the pole setting. It is impossible to predetermine the details of construction to that extent. Consequently, it should be left to the judgment of some competent man, the foreman of the construction gang.

A guy should never be anchored nearer the base of the pole than one-quarter the height of the pole and this lower limit should be shunned except in firm soil or rock.

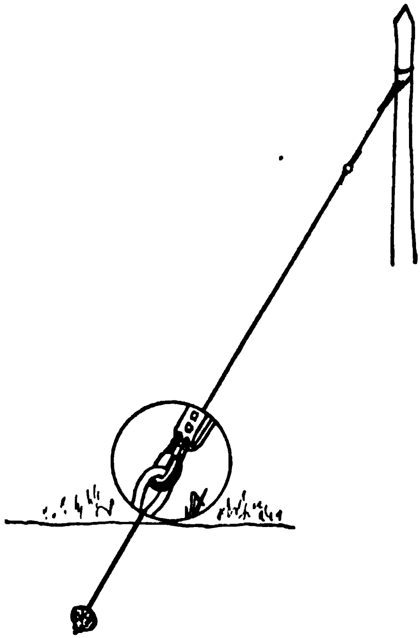


FIG. 69.—Guying by anchor log.

A much-used guy anchor consists of a log or section of an old pole 6 to 10 feet long buried horizontally to a depth of 5 or 6 feet. Through the body of this log is passed a *guy rod*, the lower end of which is threaded for a nut. Large washers furnish sufficient bearing surface between the nut and wood. The upper end of the rod has a large eye to which the guy wire is attached. The rods may be had in various lengths, such even that they may

ıke the place of the cables themselves, though this is not custom-ry. They must be installed so as to extend in the same direction s the strains will be.

A heavy stranded galvanized iron cable is looped through the ye of the guy rod and clamped back upon itself. A turnbuckle ıay be inserted at this point or higher up in the cable. The pper end of the cable is then attached to the pole either by a irect turn about it with a clamped end, as is usual with wooden oles or to a collar, as is necessary with iron poles. Figure 69 hows the details of this scheme with certain parts magnified for he sake of clearness. It is simple, direct, and inexpensive. If

FIG. 70.—Matthews guy anchor.

the buried log is replaced by a stone, it should be a large one, not that its weight is material but that the earth resistance may be as great as possible.

Numerous anchors are manufactured for driving or screwing into the earth and where the soil is suitable for their installation, they give very satisfactory results. Those which are driven depend for their holding upon either solid or hinged projectors, which fill or spread when the anchor is given a backward pull. Those screwed into place are augur-like and have no back give to be taken up. A great advantage of these anchors is the ease of installation, as two men can place one in 20 minutes in ordinary circumstances, without loosening the soil above them and weakening its holding power.

An augur type known as the Matthews Guy Anchor is shown in Fig. 70. According to a formula given by Prof. Carpenter the holding power of the earth will be shown by the expression:

$$R = 100\ DH^2$$

where D is diameter in inches of helix of screw blade and H is the depth in feet of the anchor. This gives Table XVIII as the values of strain at which the anchors would fail. Naturally, this depends greatly upon the nature of the soil.

Table XVIII.—Strains in Pounds Required to Pull Out the Matthews Guy Anchor.

At Various Depths, According to Professor Carpenter's Formula.

Depth. \ Size	5 inch†	6 inch†	7 inch†	8 inch*	10 inch*	12 inch*
3.5 ft.	6,125	7,350	8,575			
4.0 ft.	8,000	9,600	11,200	12,800	16,000	19,200
4.5 ft.	10,125	12,150	14,175	16,200	20,250	24,300
5.0 ft.	12,500	15,000	17,500	20,000	25,000	30,000
5.5 ft.	15,125	18,150	21,175	24,200	30,250	36,000
6.0 ft.	....	....	....	28,800	36,000	43,200
7.0 ft.	....	....	....	39,200	49,000	58,800
8.0 ft.	....	....	....	51,200	64,000	76,800
9.0 ft.	....	....	....	64,800	81,000	97,200
10.0 ft.	....	....	....	80,000	100,000	120,000

† It is impractical to install the 5- and 6-inch anchors at a greater depth than 5 5 feet.

* The 8-, 10-, and 12-inch anchors will not bear a great strain at a lesser depth than 4 feet.

In rock, an eye bolt may be sunk to a depth of about 18 inches at an angle of about 90 degrees from the direction of the strain, its opening being away from the pole as indicated in Fig. 71.

It is poor practice to guy to trees or buildings. The former may occasionally be necessary and then special precautions should be taken. Young or rapidly growing trees should never be used. A guy must be so attached or supported as to bear against the tree as a whole, rather than against one branch. This may be done by fastening to the tree trunk or to a heavy timber resting against both branches at the fork of the tree, and having the guy wire pass through the fork. A guy wire must never be attached to a tree by simply winding it directly upon the trunk, as this will deform if not kill the tree. Wooden slats

must be placed about the trunk and the cable will be placed upon these.

A firmly set stub is a frequent necessity in guying across a

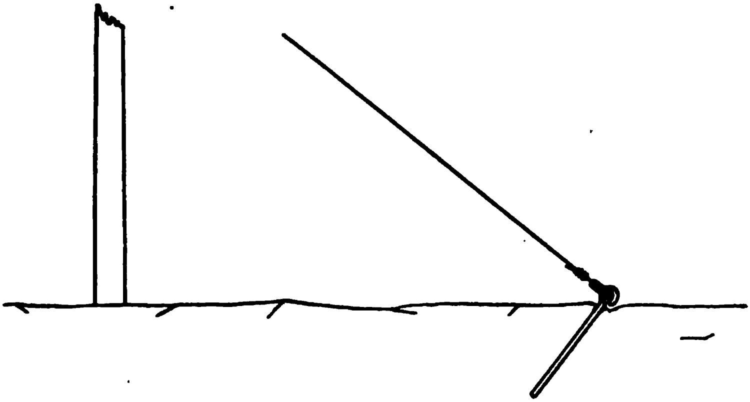


FIG. 71.—Guying in rock.

roadway, over a sidewalk, etc. This will allow (Fig 72) a short guy and still give sufficient head-room under it for passing traffic. The stub is deeply set and is given a backward rake from the

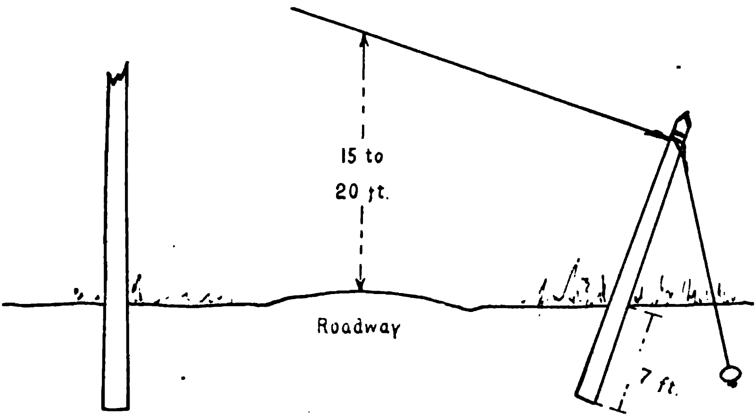


FIG. 72.—Stub guying across a highway.

pole, care being taken to avoid side slant. If the stub, the guy wire, and the anchor are not all in the same plane there will be a heavy component of the strain tending to break down the stub.

A little side give in the direction of the anchor will loosen the guy and render it inoperative. If the anchor is low enough in comparison to the base of the stub to bring nearly into a straight line the pole top, the center of stability of the stub setting and the eye of the anchor rod, instability will be the result. Even an approximation of the latter condition should be avoided.

Very long earth-anchored guys lose in effectiveness by the shallowness of their setting due to change of slant more than they gain by their approach to the horizontal. From the standpoint of anchor strength alone, a vertical setting is preferable (see Fig. 73). This, of course, is unobtainable without the stub.

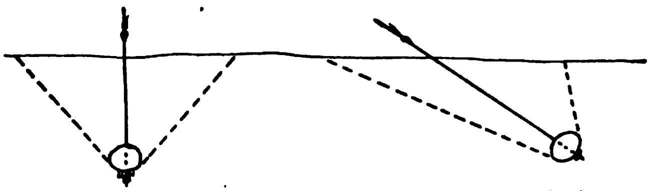


FIG. 73.—Strong and weak anchor settings.

In attaching the guy wire to the pole there are several things to note. The pull supplied by the wire is to react against a side pull caused by the line wires, upon a curve, at a corner, etc. Hence, both should be attached at as nearly the same point upon the pole as possible. The wire must not, however, make likely either a short circuit between lines or a grounding of a line. Where a cross-arm is used, the guy may be fastened directly above it. If there are two arms, it should be fastened just above the lower arm. With several arms, the best practice is to use the Y-guy, attaching one cable toward the top of the "tree" or "pole head" and the other near its base. It must be remembered that poles will bend and arms will twist. The results of different methods of setting in opposition the forces of line and guy are indicated in an exaggerated way in Fig. 74. The lighter the poles, the more distortion there will be. The pole will eventually fail at the bending point in many cases. Sleet storms will increase the likelihood of this.

Head guys are necessary at the end of a line or at corners or

sharp turns. They are run as indicated in Fig. 75. The conductor strain is in the direction away from the corner. The head

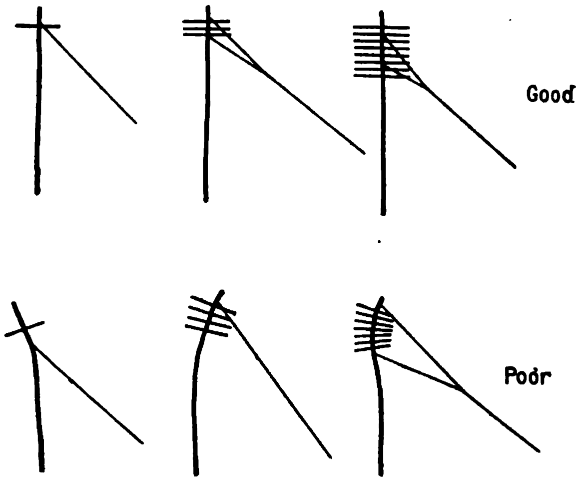


Fig. 74.—Methods of attaching guys to pole heads.

guy is so attached as to counteract this pull upon any pole head by opposing a pull from the base of the pole next toward the corner. If desired, the head guys will not run as low as to the

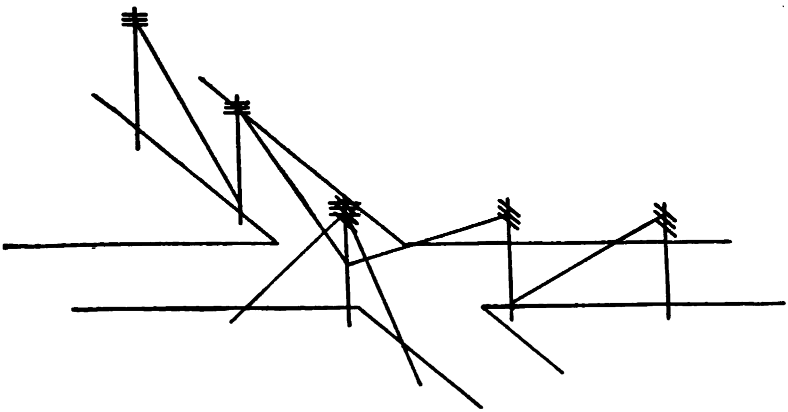


Fig. 75.—Head guying.

base of the succeeding pole but may be attached at a sufficient height to avoid interference to traffic. The corner pole, or end

pole (as the case may be), will be guyed to anchors or to stubs.

Where lateral supports are necessary and guy wires are inconvenient, they may give place to wooden braces. These are made of poles whose tops, cut slanting, are fitted to the side of the pole under the lower cross-arm and firmly bolted and bound with galvanized iron cable. The foot of the brace is bolted to a cross log or set in rocks and buried 4 or 5 feet deep. A pole may be braced on each side in this way if desired.

Wherever wood meets wood in the construction of the outdoor pole line, or where the grain is opened by cutting, the cross-arm upon the pole, the braces, the slats under a guy wire, bolt holes, etc., the parts should be given, previously to the assembling, a coat of good paint. These joints are sufficiently open to allow the retention of moisture. The grain of the wood is generally open and the result is rapid deterioration of the parts. The tops of poles should also be painted.

Cross-arms should be placed at right angles to the pole, even if the pole is given a rake upon a curve. The holes for the bolts should be determined by a straight line from pole top to base, being either upon this line, in case of single bolts, or to each side of this line in case of double-bolted cross-arms.

On curves, the arms should face the center of the curve. In approaching a dead end, the arms are placed upon the side of the pole nearest the end of the line; with unequal spans, away from the long span; away from railroad crossings. Generally in straight-away work the cross-arms alternately face each direction. This will avoid tension strains on all retaining bolts at once and lessen the liability of failures of successive cross-arms if one does give away, due to an end strain.

The arm is held in place by one or two bolts, depending upon the weight of conductors carried, etc. Usually one bolt is considered sufficient and it has the advantage of being centrally placed through the pole. A seat is made for the washer bearing against the pole upon the side opposite to the arm. Large washers, 2 1/4 x 2 1/4 inches, should be used. There are used with this construction braces of galvanized iron or steel bolted or screwed to the arm, the two ends fastened to the pole being held at a common point by a single drive screw or lag screw. Wherever drive screws are used, they should be turned for the

last third of their entrance. Lag screws should not be driven farther than just enough to start them. Single-piece angle braces, made to brace both ends of the arm, are obtainable and are very satisfactory. The increased expense is not necessary, however, although there is a greater rigidity. Care should be taken before finally fastening the braces that the arms are perpendicular to the pole. Figure 76 shows the details of a good fastening.

Double arms are used when the span is exceptionally long or the cables, etc., very heavy. If it becomes necessary to make a

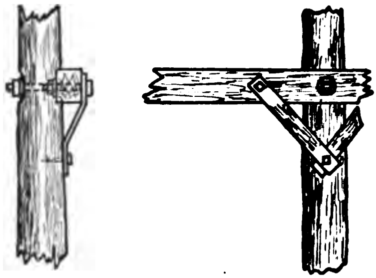


FIG. 76.—Crossarm and braces.

sharp turn without intermediate poles, double arms are advisable. They should be placed upon opposite sides of the pole and bolted together at both ends and adjacent to the pole, four bolts in all unless arms are of extra length. The arms must be blocked from giving toward each other and this may be done by inner nuts with large washers similar to nuts and washers on the outer sides, or blocks of wood cut from cross-arm timber may be bored through lengthwise and fitted in to take the compression strain of the bolt. These must be so placed that they will not interfere with the insulator pins. Each of the double arms should be braced individually.

A substitute for the double arm, where the use of the metal is not prohibited, is an angle iron into which the regular arm may be set, the whole being bolted to the pole with the iron upon the back and under side of the arm. The iron should be galvanized.

Where plain wooden pins are used, as is always the case in telephone and telegraph lines, and very frequently in power lines, the pin is inserted in the hole in the cross-arm, which has been

previously painted, and a single nail driven through the side of the arm and the base of the pin. With heavier work the iron pins extend through the arm and are held in place by washers and nuts below (see Line Insulators).

Line insulators for telephone work (see Line Insulators) and other light work are threaded internally and are simply screwed upon the pins after the latter are in place. With side groove no care need be taken to have the insulator in any certain position as the groove is the same all the way around. However, with top grooves, the insulator must be so mounted that the conductor groove is parallel to the direction of the line.

Conductor.—The conductor is wound upon a reel which may be taken from place to place as needed. The end of the wire is

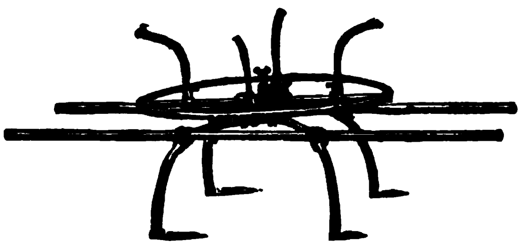


FIG. 77.—Pay-out reel.

generally handled by means of a long rope, which is attached to it. This rope is thrown up to the lineman, passed over the cross-arm, and lowered to be pulled along to the next pole. This unreels the conductor and draws it across the arms upon which it is to be placed. A "pay-out reel" is shown in Fig. 77. In taking up the slack of the line, a "take-up reel" is used, consisting of a reel mounted with its axis horizontal and having a crank handle for turning. As hard drawn copper is commonly used, care must be exercised in all its handling not to injure its surface or *skin*, because there lies its greatest strength. A slight nick caused by a lineman's tool, or a sharp kink requiring straightening will so injure the conductor that it is very liable to fail at this point. Even in tying the conductor to the insulators this must be considered.

A hard drawn copper wire should be laid in the conductor groove of the insulator on the side toward the pole except on

curves, where it is placed on the side farthest from the center of curvature. With a side groove insulator, the tie wire is looped around it in the groove having one end extending across the conductor above it and one crossing it underneath. The ends are then crossed as if to repeat this turn, at the same time enclosing the conductor. Instead, however, of taking a second turn about the insulator, the tie wire ends are crossed over and coiled about

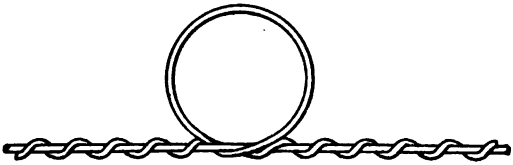


FIG. 78.—Fastening tie wire.

the conductor itself in an open helix of several turns, one in each direction. Figure 78 shows the details of this tie. It differs from the so-called Western Union joint (Fig. 79) in that the latter passes both tie ends over the conductor and the helices are closed spirals. Soft copper and iron are better fitted for the latter tie owing to its close spiral. Hard drawn copper will suffer injury to its surface if it is bent as short as is necessary for this tie.

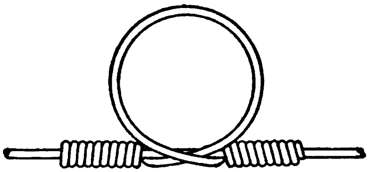


FIG. 79.—Western Union tie wire.

The conductor should not be bent around or partly around the insulator. The end sought should be to bind it firmly to the insulator but to have it tangent to the surface in the groove. Any bend of conductor at this point of support will be under heavy strain tending to make it a sharp angle rather than a curve (Fig. 80). The ultimate result is failure by breaking of the conductor at one of the two bending points, AA.

When the conductor ends at the insulator (*dead ending*) or when it is opened for a loop, the tie must be of a different nature.

The conductor is passed around the insulator, looped back upon itself, and twisted in a spiral of several turns. Otherwise, a joining device is used, either a double sleeve slipped over both strands and twisted or a clamp in case of a large conductor or cable.

A wire is spliced by means of two close spirals separated by a twist as in the W. U. joint shown in Fig. 81. As previously

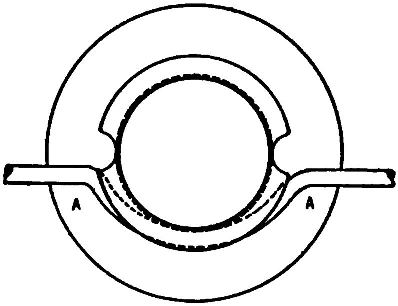


FIG. 80.—Breaking a conductor at the insulator.

remarked, however, this joint is not advisable for hard drawn copper and should not be used therewith. A much-preferred method of jointing it is by using the enclosing sleeves already spoken of. Details of this method are shown in Fig. 82, these particular illustrations being of the Cook Self-welding Wire Joint. They may be used with sizes of wires differing by as much as two numbers if desired. The metal used for the sleeve must always be the same as for the conductor, else there will be

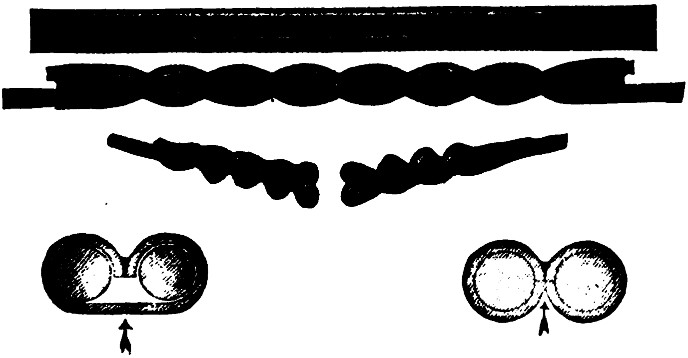
FIG. 81.—Western Union joint.

injury to the joint caused by galvanic action. For dead ending the heavy McIntyre types are especially convenient. Samples of joints should be examined in order to see that they are well made and not defective in the particulars well illustrated in Fig. 83. None of the sleeve joints is soldered and conductivity, strength, and permanence depend upon the mechanical rigidity of the construction and the intimacy of the parts. This is preferable with

hard drawn copper, as soldering, unless very carefully done, will anneal the wire to such an extent as to soften it very materially.

Dependence may be put upon these joints of from 60 to 80 per cent. of conductor strength. Some will run as high as 90 per cent., but they are carefully made and are of increased length.

A suitable method of soldering a joint is to thrust the two ends



Before twisting. After twisting.

FIG. 82.—Cook self-welding joint.

into a sleeve containing side openings, each wire extending to the center of the sleeve. The whole is then soldered. Some such joint as this is necessary in a trolley line where projecting parts must all be smooth. A twist joint of any description is out of the question there.

In telephone circuits the close proximity of two circuits to each other, as within the same cable, upon the same cross-arm,

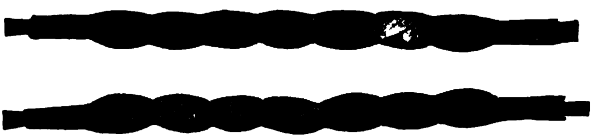


FIG. 83.—Defective sleeve joint.

etc., will lead to the undesirable result known as cross-talk unless proper precautions are taken to avoid it. Running a telephone line close to a power line may similarly introduce humming and buzzing of the receiver. There are two reasons for these annoyances, first, electrostatic induction, and second, electromagnetic induction.

When adjacent telephone lines are considered the latter of these two disturbing factors gives conditions indicated in Fig. 84. During the instant when current is flowing in line C as indicated, a whirl of magnetic lines encloses with C the adjacent line B of the other circuit. The induced current is, therefore, in the opposite direction, as indicated by the arrow, and receiver

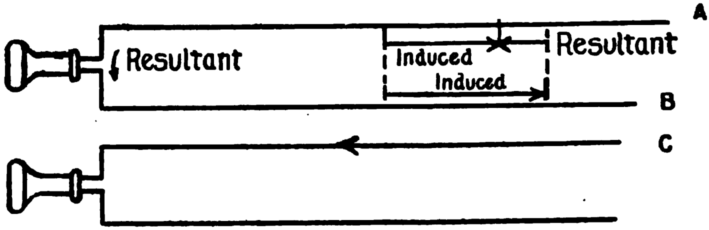


Fig. 84.—Telephone cross talk.

No. 1 will duplicate sounds present in receiver No. 2. The intensity will depend upon the mutual induction between the two lines. This effect may be overcome by so arranging the separate lines in respect to each other that similar portions are opposed to each other. This is shown in Fig. 85. These opposed sections must be electromagnetically equivalent, which generally means that one transposition at the center of the line will take

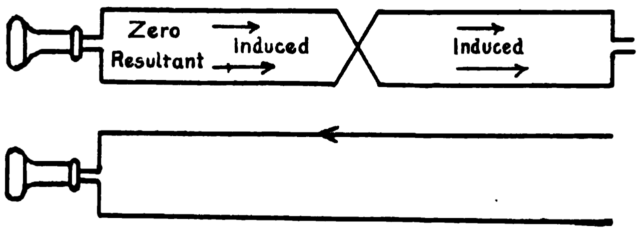


Fig. 85.—Transposition of telephone wires, single circuit.

care of this trouble. With numerous lines upon a pole, a very elaborate system of transposition must be worked out, for no two should be given identical transpositions throughout, or they have the same relation they would have without any transposing. Mr. J. J. Carty has proved by elaborate experiments (Trans. A. I. E. E., 1891) that the greater mutual effect between tele-

phone lines is due to electrostatic induction. A charge is induced upon adjacent lines (Fig. 86) which varies with every variation in current of the disturbing line. As this charge increases or diminishes in the disturbed circuit, there will be current flowing either toward or from the point *B*, either a charging or discharging current. This current produces sounds at the receivers. Transposing at the center, as in Fig. 85, will not cure the defect because it will simply allow for the neutralization of the charges partly across the central transposing points but also, in a lesser degree, through the receivers. Transposition at the one-quarter

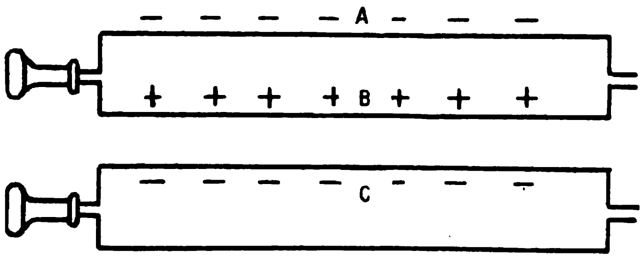


Fig. 86.—Electrostatic charges upon telephone wires.

and the three-quarters points would balance these charges against each other for one circuit, except for the oscillatory effect at the ends of the lines.

In order, thus, to do away with the cross-talk, buzzing, etc., due to inductance and capacity effects of the line, a very careful adjustment of lines is necessary because the telephone is an extremely sensitive instrument. In an extended paper upon the Transposition of Conductors read before the A. I. E. E., in 1904, Mr. Frank F. Fowle illustrates by Fig. 87 the method of development of systematic transposition. This system may be carried further than is illustrated by the figure, but generally it is not necessary to do so, as non-adjacent cross-arms may use similar transpositions.

Line *C*, Fig. 84, may, however, be a power line, one conductor of a single-phase or polyphase transmission circuit. In this case the alternating flux about the conductor is much greater and its influence is correspondingly great.

It is, then, necessary to consider not only the distance the lines

run in parallel but also, the value of current or voltage in each portion of the line, the variation in wire spacing, etc. For example, suppose we have a power line paralleling a telephone circuit for one mile. If the current in the power circuit is constant throughout the mile (no load taken from it within that section), if the distance between circuits remains constant, if the spacing of the power circuit conductors remains constant and

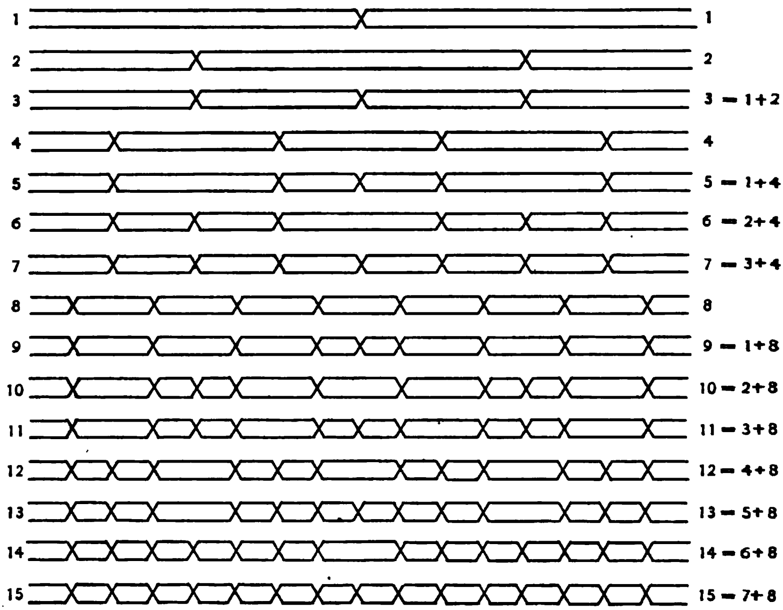


FIG. 87.—Transposition of telephone wires, fifteen circuits.

similarly the spacing of the telephone circuit, the magnetically induced voltages in the telephone circuit may be opposed to each other in half-mile sections and no disturbing current will flow. That is, a single transposition at the center of the circuit will eliminate the inductive troubles.

Again, if individual spacings and inter-distances remain fixed and voltage does not change, our line is symmetrical electrostatically and the regular transposition shown in Fig. 87 may be adopted.

If, however, at some intermediate point (Fig. 88) a change in conditions occurs, the line branches and a load taken off, the section of the line from A to B must be treated as one unit and that from B to C as another unit, each to be worked out separately. Otherwise, if a portion of AB is balanced against a part of BC any change in the relative loads of the power lines at B and C will throw the lines out of balance. With lightning circuits, the variation in load along the line is quite great but not from instant to instant. That means that an alternating current lighting circuit will be very troublesome to a telephone line, while a direct current system will cause little trouble. On the other hand, direct current railway feeders are called upon to supply rapidly fluctuating currents of great magnitude. This

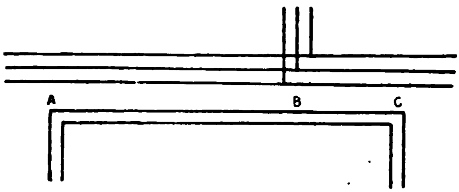


FIG. 88.—Power line and telephone line.

will cause serious disturbances in adjacent circuits. The old time telephone circuits with ground return will be so noisy in the neighborhood of railway lines that conversation is drowned, no transposition being possible.

When low-voltage, heavy current mains or feeders are carried along the same street as telephone wires, there will be disturbances even if the two systems are on opposite sides of the street. Transposition may be resorted to or twisted pairs of wires for each telephone circuit will assist. If the power cables are spread with considerable distance between them (in case of a line and its return) and can be closed upon each other, there will be a marked improvement of conditions. The power circuits should not be spread any farther than is necessary.

It is frequent practice to carry railway feeders or lighting circuits upon the same poles, with the telephone lines, the latter being above the feeders. This is the source of much trouble unless the likelihood thereof is recognized at the outset and precautions taken.

It is necessary, however, whatever the scheme of transposition, to have it rigidly adhered to. No variation in distance can be allowed or confusion of lines is the sure result. A lineman cannot follow an irregular arrangement 10 poles without becoming lost in the maze. He must know what the design is and that it is reliably and fully carried out. Then, reference to the pole numbers with a chart for the transposition scheme for one section will give him the means of exactly locating each wire and recog-

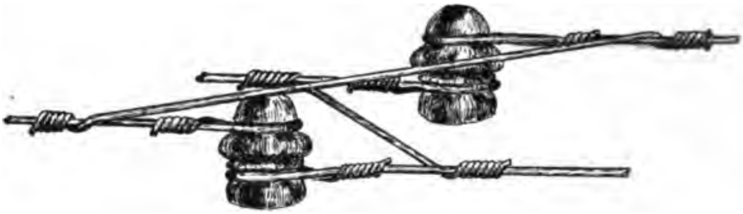


FIG. 89.—Square transposition.

nizing each circuit. It may take several miles for the completion of one section in which the complete design is carried out. Then it will be repeated in the next section of the same length. The actual transposition may be accomplished by opening and dead-ending the two conductors to be interchanged, at special double-grooved insulators. The exchange is then made by jumpers crossing from each incoming line to the other outgoing line. This method (shown in Fig. 89) has the disadvantages that it cuts the line and the transposition cannot be shifted from one

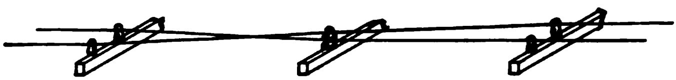


FIG. 90.—Single-pin transposition.

pole to another except with considerable labor. It has the advantage that it is accomplished at one pole and may, therefore, if occasion demands, be repeated at each successive pole.

Another method used is called the single-pin transposition. The two lines are led to the same insulator, one above the other. They proceed from that point in transposed order. This is illustrated by Fig. 90. This method does not open the lines and the transposition may be shifted from one pole to the next with-

out much labor. It is simple in application, requiring no cutting, dead-ending, splicing, simply the ordinary tying at the insulator. It introduces, however, new stresses upon the pin and it can occur only at every second pole. As the pins may be heavier, with the heavier insulator, thus meeting the increased stress, and as the transposition of conductors at every pole is a very unusual demand, this latter method has been rapidly growing in favor.

When the double cross-arm is used on long spans, etc., the transposition is made between the two arms by the square method, using single-groove insulators only.

Railway Lines.—Many of the preceding details enunciated in the consideration of aerial telephone lines are applicable to the installation of power lines. All the more is this true if we speak only of low potential circuits. Here the number of conductors is limited to two, three, or six, but each lead is heavier. The construction of the line as a whole will be more sturdy and rugged.

Local railway power circuits are carried on shorter poles than are necessary for telephone work. It is customary to have the trolley wire 15 to 18 feet above the tracks and the poles are of sufficient height to carry them and such feeders as are required.

There are two standard methods of construction for supporting the trolley wire, span supports and bracket arms. Each of these is further divided into direct support and catenary construction. When wire spans are used, poles are placed upon both sides of the single- or double-track railway, being opposite each other along the way. One of these sets of poles will perhaps be taller than the other in order to carry feeders. They are of wood or iron and may be set with a little outward rake. This is not always permissible, as a marked contrast between the line of the pole and perpendicular lines of buildings is to be avoided. At a point no less than 18 inches from the top of the pole a bolt hole is bored and an eye bolt inserted, being held by a nut over a large washer. Into the eye is inserted the span wire or cable which is bent back upon itself and securely fastened. Near to each end of the span wire is placed a strain insulator. At such a point as to bring it over the center of the track is inserted an insulator bearing a supporting ear for holding the trolley wire. For double track two such suspension insulators will be used. Standard forms of strain insulators and suspension insulators are shown in Fig. 91.

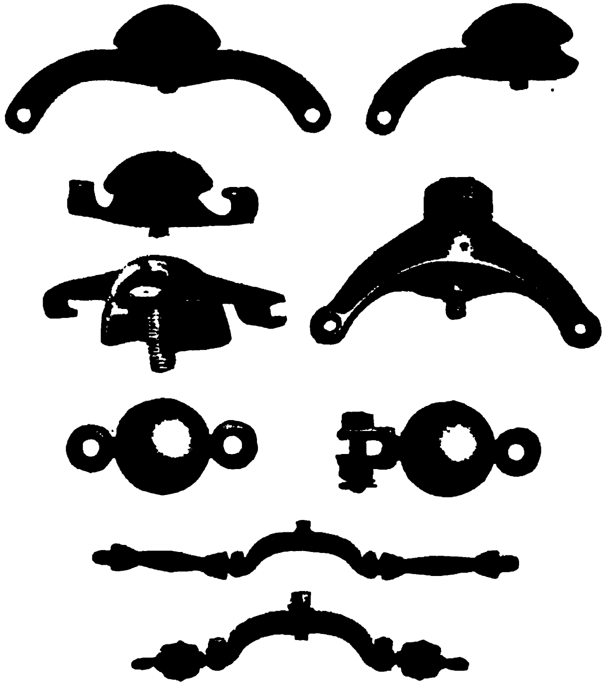


FIG. 91.—Trolley wire insulators.

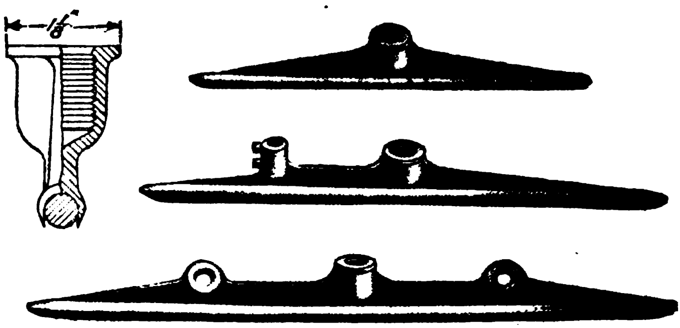


FIG. 92.—Soldered ears for trolley support.

The double-armed suspension insulators illustrated are used in regular work. The single-armed are used on curves or elsewhere where a one-way pull is to be supplied.

The ears attached to these insulators for direct connection to the trolley wire are of two general types, depending upon the kind of wire used. For a circular trolley wire an ear is used which

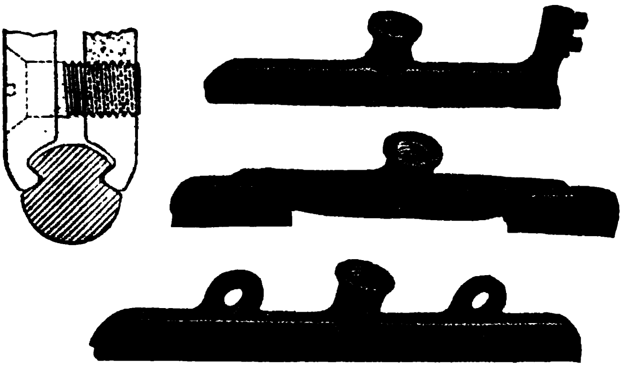


FIG. 93.—Clamping ears for trolley support.

extends down part way around the wire upon each side and is soldered thereto. Their office may be added to by making them feeder points or connectors for guy wires (Fig. 92). When the trolley wire is of the grooved or figure-8 type, the ear does not need to be soldered to it but may be made to clamp it tightly as in Fig. 93.

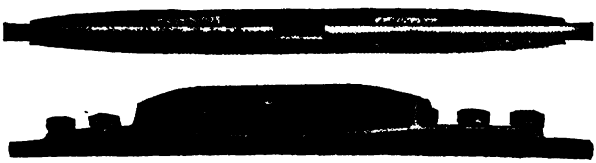


FIG. 94.—Mechanical splicing sleeve and section insulator.

Splicing round trolley wire is accomplished by soldering into a splicing sleeve, as already mentioned, or by the use of a mechanical splicing sleeve as shown in Fig. 94.

Frequently the opposite kind of a joint, an insulating joint, is desired in order to break the wires into sections. Then, a *section insulator* is used, a device which provides an insulating run-

way for the trolley wheel as it leaves contact with one section of the conductor and approaches the new section. Figure 94 also shows this type of joint.

Where the trolley wire is to be divided or crossed, a sleeve is inapplicable. Frogs and crossings are necessary for this service. The frogs are made with two or more branches as required, and likewise, with different angular divergences. They are also supplied with two or more eyes for pull-off guys. Best practice

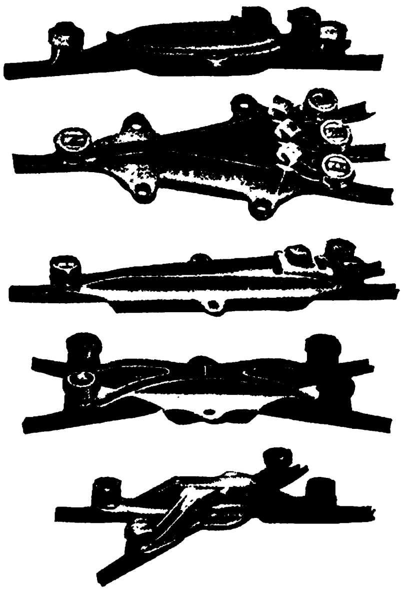


FIG. 95.—Trolley frogs and crossings.

is to depend upon their mechanical attachment to the trolley wires rather than to soldering. Figure 95 contains a group of trolley frogs and crossings. The crossings differ from the frogs in the detail that provision is made that each trolley wire shall continue past the point of intersection in its original direction, 90 degrees, 35 degrees, etc. Generally, these crossings are accomplished without insulating the two trolley wires from each other. Where insulation is necessary, a special crossing is required which will not break either circuit but will separate them from each other.

Owing to the fact that the suspended conductor must follow very closely the curvature of track, the guying of a trolley wire is very important. Straight lines are anchored about every 2000 feet to avoid pulling down in case of break, etc. This is practised also on grades and at ends of curves, Fig. 96. At curves, the side guying is very carefully planned, strain points occurring close together. It is not necessary to have separate guy anchors or stubs for each guy line, but they may be combined in groups depending upon the nature of the curves. One-way curves and two-way curves with crossing are illustrated in Fig. 97, for single track. For double track, the trolley wires are tied together and a little more elaborate side-guying is practised. It will be noted

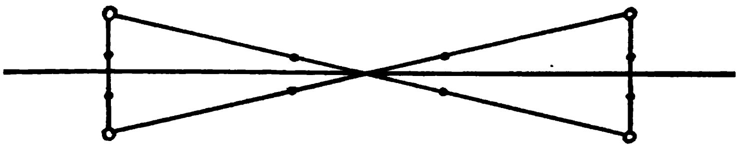


Fig. 96.—Anchoring trolley wires.

that the conductor upon a curve does not center with the track. This is due to the slight side swinging of the trolley pole as the car rounds the curve, the amount of which depends upon the curvature of the track, the length of trolley pole, and the height of conductor above the car roof. The allowance may be as much as a foot at the center of a curve of 40 feet radius.

Feeders carried along upon cross-arms or brackets upon the poles are tapped into the trolley wire at required intervals. This is best done by splicing a jumper to the feeder. The jumper is then supported upon a bracketed insulator in order to transmit no strain to the feeder itself. Moreover, it is never carried upon a cross-arm insulator, as this would inevitably put it in the way of subsequently installed feeders. If cross-arms are installed their pins can be put to better use than that of supporting jumpers. The feeders are carried above the span wires. Hence the jumper will be brought downward from its point of connection, then, after attaching to its insulator, it will be carried out along the span wire to the trolley wire and attached to that at a feeder ear, already illustrated.

Where heavy feeders leave a station, where square corners are

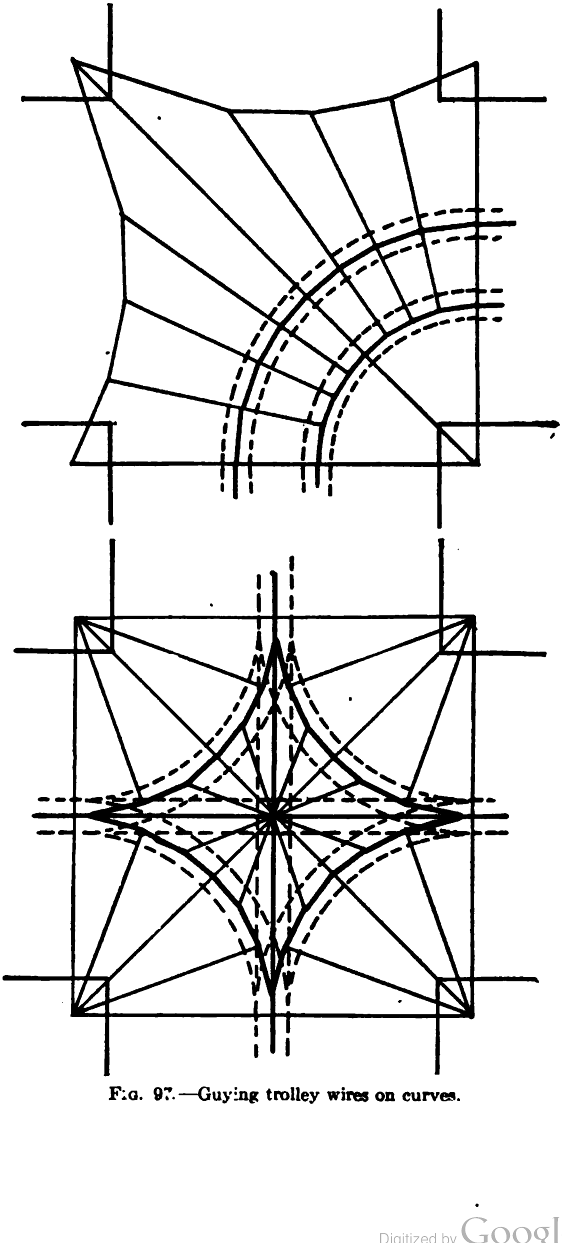


FIG. 97.—Guying trolley wires on curves.

turned, or dead ending points, they may be most readily supported by means of clamps which will take the strains. This method of installation is easily put up, economical of conductor and of labor, easily shifted, strong and reliable, and neat in appearance. It allows for very flexible application, owing to its simplicity. The actual installation utilizes a cable clamp which is bolted to the cable so tightly as to be able to carry the full strain upon the line. An eye bolt in the cross-arm receives this strain through a strain insulator. The details of a Matthews'

FIG. 98.—Matthews' cable clamp.

clamp are readily seen from Fig. 98, which shows a right-angle turn on the inner side of the cross-arms. Figure 99 shows several of the applications of this device. The cuts are largely self-explanatory, being

1. Inside corner.
2. Outside corner.
3. Right-angle tap.
4. Slack for future use.
5. Dead ending at underground entrance.
6. Comparison between use of clamps and spliced corners.

When a pole can be placed close to the side of a railway track or between the two tracks of a double-track system, it is much to be preferred to use bracket suspension of trolley wire instead of the span construction already described. The construction of side pole line and of center pole line are exactly similar in all engineering features. Side brackets can be used of sufficient length to serve for double-track roads, but this is not very common practice.

The poles may be either wooden or iron but brackets should invariably be of metal. The bracket arm extends horizontally outward from the pole about 9 feet and usually has a guy rod running from its outer end to the pole top. A strut is sometimes used in bracing it more firmly. When the guy rod is not used, the strut is necessary and vice versa. It is not best practice to

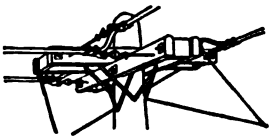


FIG. 1.—An inside corner turn with Matthews' cable clamps, using "bridle guys."

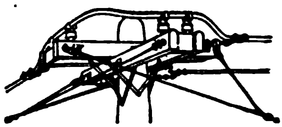


FIG. 2.—Outside corner turn, using Matthews' clamps and the "bridle" guy.

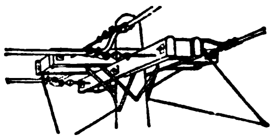


FIG. 3.—An inside corner turn with Matthews' cable clamps, using "bridle" guys.

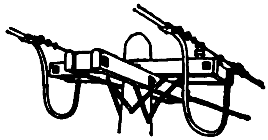


FIG. 4.—Showing method of leaving slack in line for future use by the use of Matthews' clamps.

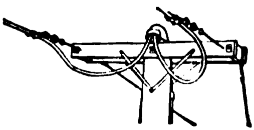


FIG. 5.—Deadending two cables at U. G. junction pole by means of two Matthews' cable clamps.

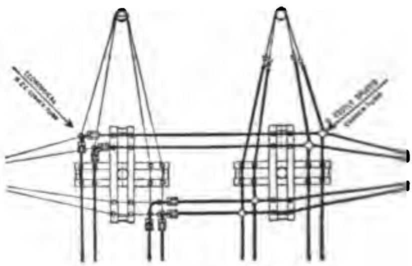


FIG. 6.—A comparison.

FIG. 99.—Applications of Matthews' cable clamp.

support the trolley wire rigidly at the end of the bracket by means of an insulating support. This makes a *hard spot* in the line and is injurious alike to line and trolley. Generally, the bracket supports a flexible galvanized steel cable, from which the line may be suspended. Some standard brackets are shown in Fig. 100. These are very plain and neat in appearance. Many

more elaborate and ornate designs may be obtained for use in city streets if desired. Angle irons may be adapted to this use very readily and make a very serviceable arm, probably just as satisfactory as the tube arms illustrated.

As all points of support of trolley wires by the described methods of construction occur only opposite the poles, there is a decided sag to the line between poles. This causes the underrunning trolley to rise and sink periodically. With high-speed running the result is that the trolley will separate from the con-

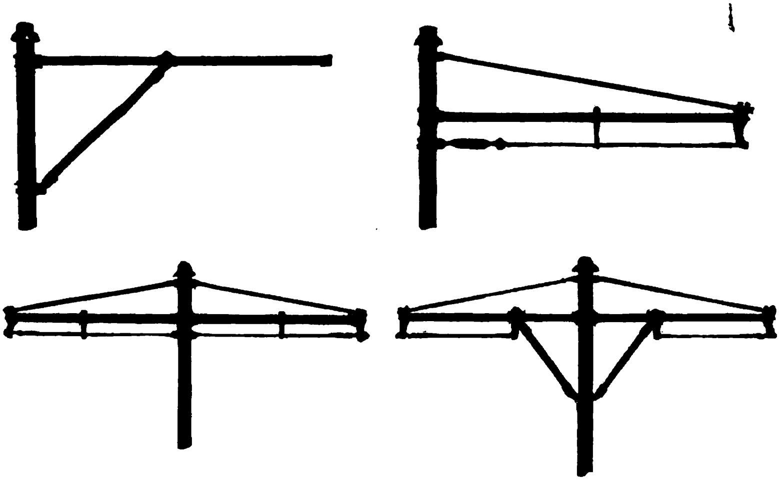


FIG. 100.—Side and center pole brackets.

ductor by jumps and the contact is insecure. With the development of high-speed interurban railways there has been brought into use the double suspension called *catenary suspension.* Pole line, spans, brackets, etc., are fundamentally as for direct support. The trolley wire is hung from the messenger wire or catenary by means of hangers of graduated lengths, thus maintaining a practically uniform height for the conductor. No attempt is made to insulate between trolley wire and messenger, thus increasing the conductivity of the line. In span work, the insulator is inserted as previously described in direct suspension. In bracket work, the messenger runs over the bracket arm and is supported upon a regular pin insulator of sturdy design.

There is increased difficulty, however, in guying. Anchoring

requires not only the four side pull-offs from the messenger but also two extra leads, each running from the pull-off point of the messenger to a point on the trolley wire at the foot of the adjacent hanger. Figure 101 will make plain many of the details including anchoring. Upon curves with pole line inside of the curves, insulating braces are used running directly to the trolley wire and supported at the rear end against the bracket. If the pole line is outside the curve, wire side-spans from one pole to the next

FIG. 101.—Catenary anchorage.

may be used to support pull-offs to keep the trolley wire over the track. These points together with feeder connection are illustrated in the group Fig. 102.

For very heavy construction with more than two tracks, it is advisable to use bridge spans, built of latticed iron. Here, too, the use of *double catenary suspension* is practised, as by the New York, New Haven, and Hartford Railroad. This consists of two messengers similarly carried upon pin insulators over the lower member of the bridging. A trolley wire under-runs the two and

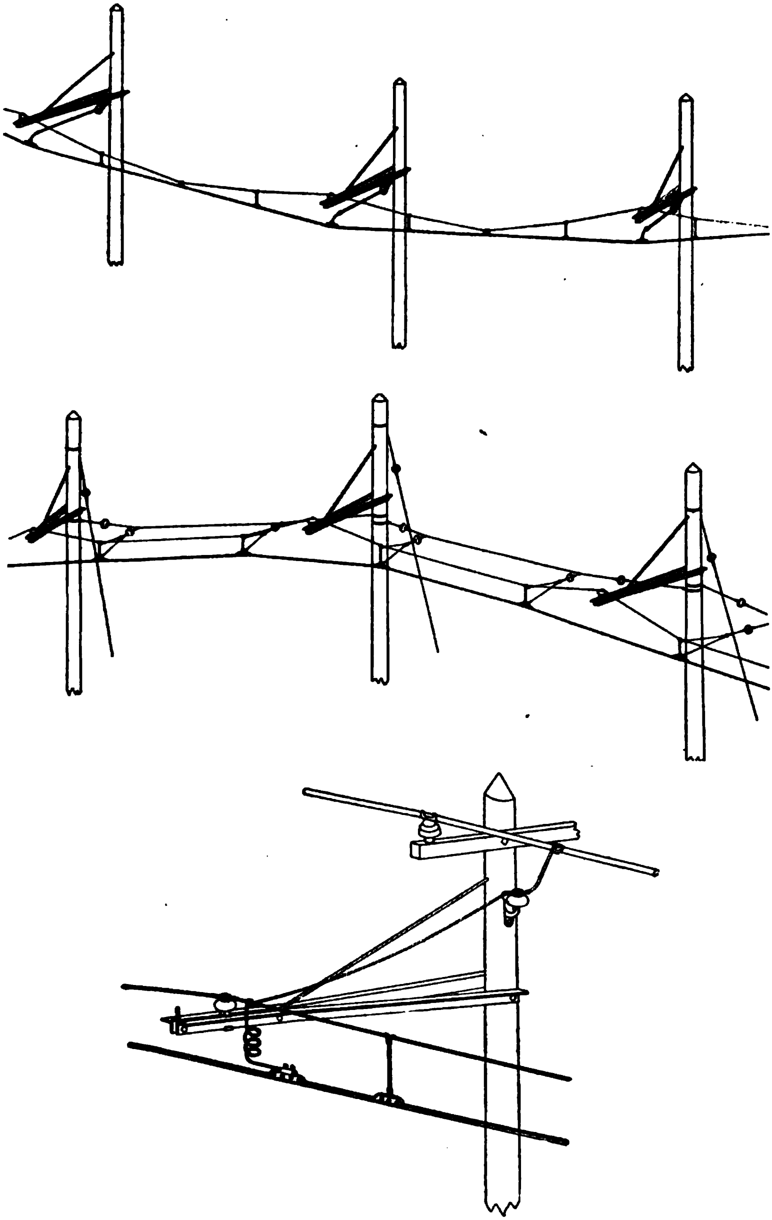


Fig. 102.—Details of catenary construction.

all three are bound together at regular intervals by triangular forms built of piping. The triangles are of decreasing size from the bridge toward the center of the span at which point the sides

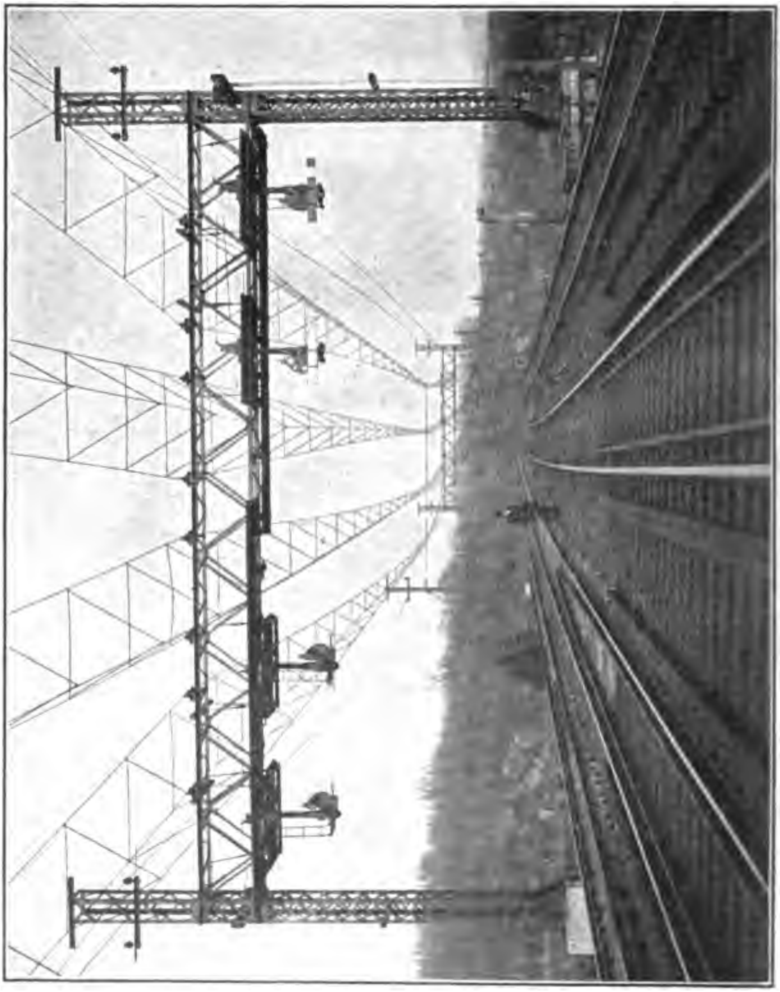


FIG. 103. Double catenary, New York, New Haven and Hartford Railroad.

are less than a foot in length. Figure 103 gives an idea of this construction as practised by the above-mentioned railway.

These designs are found to give much better results than the

ordinary suspension for interurban high-speed traffic. Abroad the *multiple catenary* has been used. The first catenary supports a second catenary, which in turn supports the trolley wire. The lower catenary and the conductor are very nearly parallel, as one catenary suspension gives fairly uniform direction to the second messenger.

The bonded track furnishes the return circuit for railway systems and it is generally considered sufficient to meet the demand. Very frequently there are water mains laid in such a way as to furnish a parallel path for the current. The use of the iron piping as a conductor does not injure it at all. So long as current remains in the water pipe no damage is done. But at the point where the current leaves the piping the metal is attacked and eaten away by electrolysis. This action is aided by the presence of moisture and certain salts in the earth which make the earth resistance less. Wherever it is found that this injury is occurring, steps should immediately be taken to relieve it. If it is well established that the return current leaves the piping at certain definitely determined points, return conductors may be run from piping to rails at these points. This is a very simple condition of circuits, however, which does not often occur. Unfortunately, the return of current from water or gas mains is not from easily determined points, but occurs at many widely distributed and extended portions of the system. When it is assured that there is electrolysis, there should be an extended inspection to determine its cause. Rail bonding should be tested, length of return circuits, and substation location studied. Other corrective measures failing, it remains to put in a system of negative feeders for the return circuit. This must be planned after having located as nearly as possible all the points or localities where the unnatural corrosion occurs. For heavy traction, negative feeders are sometimes installed in parallel with the rail, simply adding to the rail network a network of copper conductors.

Power Lines.—Power transmission utilizes something of the same detail in the construction of lines that has already been described for telephone and telegraph service. The poles are of the same woods, are set the same way, cross-arms are similarly placed, pins are inserted in cross-arms for insulators, the lines are guyed

upon the same principles. Everything is adjusted to meet whatever new demands may be made by the change of conditions, namely, instead of numerous small conductors carrying small currents at low voltages, we have large currents, high voltages, few wires, but of larger cross-section and weight. Spans may increase in length to meet certain requirements. Insulators are of the heavier type. Standard copper conductors 1/2 inch in diameter (250,000 C.M. cross-section) are heavy enough so that upon single pole line construction the pole spacing should not exceed 100 feet. For lighter conductors a greater spacing may be used without special construction. Numbers 0 to 0000 may be strung on poles 125 feet apart.

In splicing heavy wires the enclosing sleeves should be used. They are obtainable in all sizes and for copper or aluminium. The use of special tools for twisting these joints greatly facilitates their preparation. No solder is used with them and consequently there is no weakening of the conductor due to annealing.

The wooden pole groups described in Chapter III are the next steps in increasing the strength of the pole line. Of these, the A-type may be conveniently assembled before erection. Consisting as it does of two poles bolted together at the top, with a spread at the bottom of about one-eighth of its height, with a double cross-arm bolted through and through, the whole unit lies in one plane and can be assembled flat upon the ground. It is raised by horse-power as it is twice as heavy as the single-pole construction. Any work that can be done before raising, such as fitting, assembling, etc., is much more easily, quickly, and efficiently done if it is completed upon the ground. With some more elaborate structures it is found preferable to do the fitting upon the ground and leave some of the fastening to be done after the parts are up. With two parallel poles interbraced, the erection may occur either before or after the bracing and placing of cross-arms, as determined by the convenience in handling the increased weight of the combined parts. When raised individually, especial care must be taken to secure proper alignment of poles, spacing, etc. Cross arms should not be bored until fitted after erection in this case.

Where the second or third poles are used as braces, rather than as part of the tower proper, they may be fitted before

erection, but final adjustment should be made after the pole is in place.

Perhaps the most convenient method of handling the double A or ridge pole tower is to assemble the two halves, each consisting of the two poles which are parallel, bracing the poles upon each other. The two halves may then be raised separately and the pole tops brought together and held by means of blocks bolted upon each side at the top. The cross-braces, struts, tie-rods, and cross-arms are then added. In general, well inter-braced members of a tower may be handled together if it is deemed desirable to do so.

Iron or steel towers are shipped in a completely disassembled condition, but they are generally fully assembled before raising. Take, for instance, a four-cornered windmill tower type. One method of handling it is to assemble it by parts. The four corners are laid out in pairs and all stays and braces added to each pair. Each of these two opposite sides is then stood upon edge with tops together and bases separated by the proper amount for fixing the cross braces. These are then added, completing the tower. All this should be done upon the uphill side of the site. Or when the cross bracing is so designed as to make only a few tie points between corner posts, the tower may be assembled in quarters, the quarters into halves, and the halves into a complete unit.

The towers are then fitted with cross-arm pins and the insulators even may be cemented in place.

Insulators, if built in several pieces, should be cemented together by the manufacturer before shipment. This is always done unless the purchaser especially states his contrary desire. It insures better and more uniform results to have this done. If they are too heavy for convenient handling, they may be obtained in parts, however, to be assembled upon the ground by the purchaser. Neat Portland cement is generally used for this purpose.

For wooden pole towers, the setting of each leg may be done as already discussed for single poles, as regards base plate, concrete base, etc. Occasionally serious difficulties are met. One of the most unique methods that has come to the author's attention is described by Mr. R. D. Mershon in Trans. A. I. E. E., 1907.

The wooden A-type of tower was used by the Niagara, Lockport, and Ontario Power Company in crossing the Montezuma swamp. No ordinary method of setting the poles seemed feasible so that a surface setting was determined upon. A giant cris-cross was constructed of four line poles and placed flat upon the ground. The base of the erected A-frame was spiked to this structure and both legs were braced from about the one-third point in each way in the direction of the line. This large base gave stability which was very materially increased by fastening large plank boxes upon the ends of each pair of base poles and filling them with stones.

With metal towers, the most permanent construction is obtained when concrete bases are prepared for reception of the legs. These bases must partake of the nature of anchors as well as base plates. A heavy side strain upon a tower tending to tip it over imparts a downward pressure upon two pedestals and a lifting strain upon the other two. The magnitude of the upward pull is a function of the size of the base of the tower from side to side. A tower with small base will pull up much more readily than one with large spread.

A large reinforced concrete base plate (say 4 feet square by 1 foot thick) buried 5 or 6 feet in the earth will give a very secure foot plate. Angle irons may be imbedded in such a plate and to them will be fastened another angle iron running to a point above the surface of the ground. This corner anchor iron is protected by a heavy concrete body giving more weight and strength to the anchorage. These pedestals are built directly in place, of course, and are accurately spaced and set to grade. The angle iron extending above the ground surface is the stub to which the foot of the tower will be secured by bolting. Corner or angle towers, end towers, etc., must be set with larger anchorages.

Concrete construction is not considered necessary in all cases. In fact, the reverse is the case in a great majority of instances. A very satisfactory setting is accomplished by using a stub consisting of an angle iron secured to a metallic foot plate. This is carefully buried in heavily tamped earth or surrounded by rocks. The metallic bed plate, even, may be done away with if heavy cross pieces are used as anchorage and a substantial stone set for the foot plate. When concrete is not used for the standard

towers it should be used for corner towers, extra length spans, etc.

In erecting (see Figs. 50 and 52) the two legs of the tower which are resting upon the ground are situated near their stubs, having been assembled in that position. Each one is securely bolted to a roller. The ends of each roller rest in sockets in a trunion which is staked to the earth securely enough to stand the severe strains which come upon them in holding the tower foot in place as the structure is raised. A pole mast is erected, from the top of which block and tackle running to the tower give the means of pulling the tower to a vertical position by using horses upon a straight-away pull. The rope should run from the top of the mast to a

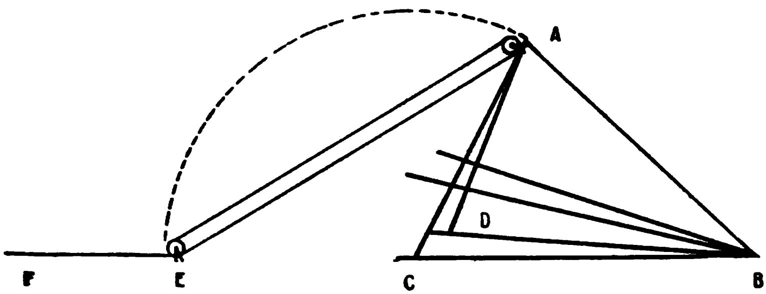


FIG. 104.—Movable A-mast, for tower erection.

pulley at its base in order that the pull of the team may be applied horizontally. The pole mast may give place to the A-mast.

Without the use of a fixed mast, a movable A-mast is convenient. This will consist of a well-braced A-frame of sufficient base spread to allow it to be fastened to the legs of the tower, Fig. 104. The two legs of the frame are then fastened as at *CD*. Ropes running from the upper part of the tower, *B*, to the mast top, *A*, are of fixed or adjustable length. Another rope from *A* continues to another pulley at *E*, any number of turns being used between *A* and *E* as desired. The A-mast will move with the tower, being nearly horizontal when the tower becomes upright. It is necessary to have the angle between the vertices of tower and mast not over 90° in order to allow for complete erection unless the distance *AB* is adjustable. The distance *EC* should be

very little greater than the radius AC. The legs of the tower are braced upon rollers as before indicated and side guys must be used.

Various other methods are used for the tower erection.

Back and side guys should be attached to a tower in raising it and should be manned and kept taut continuously. They, too, may pass through pulley blocks if it is considered necessary in view of great tower weight.

Permanent side guys upon towers are unnecessary except in unusual circumstances. In case of very unstable conditions of foundation they may be permitted. It is customary, however, to rely upon the tower itself which is designed to give proper security.

Guying forward and backward is frequently practised, however, in order to give greater strength to the line if conductors should break, giving an unbalanced tension of all cables upon one tower. When used it is installed about every five or six towers.

The work of putting up towers is not handled by one gang of men, but is found to be easily divided up into several stages or steps—the number of gangs required depending upon the type of the tower used. Supposing the lines to be laid out, stakes set for towers, etc., the material will be shipped to nearest points and hauled out and distributed at the individual sites by one gang of laborers. If the towers all are standard with parts interchangeable, the sorting of parts is facilitated. With special towers, great care must be exercised in making the proper distribution of members as well as placing a given tower upon the site for which it is intended. In fact, all parts of a tower may best be numbered as to the location in the line, thus individualizing it from the very first. Even in standard towers, this will avoid the likelihood of duplication of parts, etc., in the separation of the shipment before hauling.

A second squad of laborers will dig all holes for the corner anchorages. This requires that in setting stakes for the towers each corner must be located so that no farther measurements need be made by the hole diggers.

Another squad will set the corner anchors. This gang must be under the direction of a man capable of judging the foundation

value of the soil. Any tendency toward quicksand or marshiness will demand special care. If no plan of setting the foundations promises to be successful a last resort may be to shift the position of the tower. This should be done only upon the authority of the engineer in charge of the construction, and he should exhaust all ordinary expedients to avoid it. Frequently, however, a shift of only a short distance—a few feet—may greatly relieve the serious features of construction upon quicksand. As the anchors are set they must be put in accurately at the required distances apart, in proper position for fastening to the foot of the tower and exactly to grade in order not to tip the tower or give it a skewing stress in forcing it into position to insert bolts.

One gang may be used to assemble the towers as far as can be done without raising any of the parts, that is, with pieces lying flat upon the ground. A second assembling gang supplied with a little rigging may finish the task. This will include combining the parts into a finished tower. They must be fitted, therefore, to handle heavy sections, either quarters of the tower or perhaps halves. Cross-arms should be added by this squad.

If insulators are to be attached before raising the tower, another small group of men is required for this duty. This, in particular, is a job that may be only half done and still look all right. Competent and reliable men should be used here.

The erecting gang constitutes the next division, and to it falls the duty of erecting and fastening the structure. This is the heaviest work of the construction of the whole tower line. If two lines are going up side by side in order to carry two circuits, independently, the erection of one tower will give a mast for the erection of the second.

The stringing of the conductor by linemen will be accomplished by paying it out in full reel lengths. If there are to be three conductors upon a tower, all three will be strung out at the same time. They may be temporarily supported upon cable rollers to allow pulling along and tightening without injuring the cable or conductor surface. After being loosely stretched one end of each cable is firmly anchored. Tension is applied to the cable at or beyond the second tower until it is brought to its proper sag and it is then anchored at the second tower. The other two

conductors are treated similarly and the linemen proceed to the next span.

In determining the proper sag, several things must be taken into account. If the conductor is aluminium, it must be given more sag than a copper conductor would require. Temperature, at the time of adjusting, height of towers, length of span, and relative altitude of towers, all influence the tension applied or the sag allowed (see Chapter X). When the amount of sag has been determined the conductor is pulled until the dip of the lowest point of the span brings it into line with points upon the two towers lower than the top of the insulators by the required amount. That is, if a sag of 8 feet was to be allowed in a certain span, the lowest point of the conductor would come into alignment with two points, one upon each of the two supporting towers respectively, each point being 8 feet below the cable groove of the insulator. This is a much used method.

Another and perhaps a little more logical procedure is to predetermine the allowed tension upon the line for the known conditions. This tension is then supplied through a dynamometer and the cable is clamped in place. Here, too, the same features will govern in determining the tension as were considered in ascertaining the proper sag. It must be remembered, however, that the direction of change in altitude affects the pull. That is, a certain span upon a heavy grade will have a greater tension if it is measured at the upper end of the span than if it is measured at the lower end.

Ties or clamps may be used in fastening the conductor to the insulator. A very secure method of tying in an upper groove is to pass the tie wire diagonally over the conductor along the top groove. Each end of the tie wire is then bent downward, passed under the conductor, and laid in the side groove half-way around. It then takes an upward sweep after passing under the conductor around which it is given several close turns in ending the tie. This is a very easily constructed tie and has given good service.

Another tie partaking somewhat of an anchoring rather than a rigid tying is made by using two separate tie wires at each insulator. The first one loops around the insulator head and both ends are carried to a point of the conductor at a little dis-

tance from the insulator. The tie wire is then twisted about the conductor in a close spiral. The second tie wire is similarly applied in the opposite direction from the head.

On the other hand, there are numerous clamps which give very satisfactory results. One of these, known as the Clark Insulator Clamp, is illustrated in Fig. 105 which shows the method of application. Figure 106 shows a clamp to be used when the conductor is laid in the side groove at angles in the line. Here, naturally, the insulator is always inside the curve.

Fig. 105.—Clark standard insulator clamp.

Fig. 106.—Clark angle insulator clamp.

In using the suspension type of insulator, the successive sections are held together by links, short cables of special composition, or by special ropes. If the latter can be protected by special treatment from rotting out they will probably prove the better support, as continued swaying and jarring crystallizes the metallic link and weakens it very materially. The links may be closed by bolting, clamping, or tying. The conductor is suspended from the lowest one of the series by a short link attached to a clamp which bolts securely to the conductor itself.

This type of suspension may be applied in another way. Instead of a string of sections pendent from the cross-arm and acting as a swinging support, the series may be drawn up tightly as strain insulators, the conductor looping loosely below the arm and passing to the next span which is similarly supported from the further side of the same arm. The former method is preferable as the latter requires twice as many insulators, affords twice the leakage path to ground. Upon curves, however, the latter

method must be used in order to avoid side swinging. The practice is to use the first scheme upon straight-away work and the second upon curves, or for other special reasons as branching of circuits, etc. Even in straight lines, however, the strain type must be installed at intervals or at danger points. The units used for these different positions differ in shape, as already shown, for weather protection.

When a line is to be dead-ended, one standard plan is to attach it to a strain insulator set between two cross-arms as shown in Fig. 107. This method is good up to about 35,000 volts. The

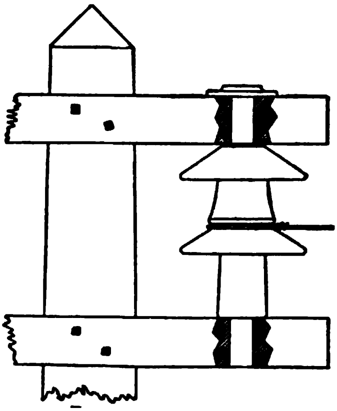


Fig. 107.—Pin-type strain insulator for dead-ending.

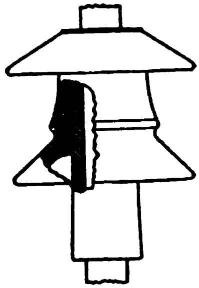


Fig. 108.—Strain insulator showing pin opposite the wire groove.

strain would easily crush an insulator unless caution is observed in mounting the insulator upon the pin. The inner surface of insulator must make contact with the pin at the point directly under the wire groove, thus transferring to the pin by compression upon the porcelain the entire strain taken by the support. (see Fig. 108). For strains of over 12,000 pounds the pull should be divided between two or more insulators, mounted either upon the same cross-arms or upon poles, the one set a few feet back of the other.

The link type of insulator very readily lends itself to this application of dead-ending. A number of them may be placed in series, thus raising the insulation value to any figure desired. A very neat application of these insulators for dead-ending a line

at the power-house is indicated by Fig. 109. The conductors of the Schaghticoke-Schenectady transmission line in leaving the power-house pass directly over the river. As the river bank back of the station is steep, the leads run over the flat roof of the power-house and are dead-ended by strain type link insulators, two in series. The dead cables run directly to short lattice iron poles or stubs set in concrete in the side hill at an elevation approximately that of the station roof and continue to anchors in the ground.

The link insulators are inserted just above the back station wall and the conductors are connected to the lightning arresters

Fig. 109.—Anchoring the Schaghticoke-Schenectady power line at the power-house.

by pig tails from the live wires running down to the roof. The strain met here is only for the one span, however, as upon the first tower across the river strain insulators of the same type are used in each direction, with the conductor looping below the arm.

It has been the general custom to arrange the three wires of a three-phase transmission line at the vertices of an equilateral triangle. This is standard practice in order to avoid unbalancing of the line itself and serious mutual induction with other lines. The cause for this arrangement is not difficult to understand, as the arrangement of lines is wholly symmetrical in respect to each other.

With one three-phase circuit per line, this arrangement is generally accomplished by a pole top insulator with two more insulators upon opposite ends of a single cross-arm. The spacing

between conductors will thus be adjusted by raising or lowering the cross-arm and shortening or lengthening it by proper amounts. Roughly, the distances used may be said to be as many feet between conductors as tens of thousands of volts. Frequently, however, a spacing of 6 feet will be found with only 40,000 volts, initial construction taking into account a contemplated rise in voltage at a later time when the demand for power has increased.

This arrangement leaves the conductors in an open relation to each other and each one is easily accessible for repairs. A single line, being symmetrical, requires no transposition of conductors so far as its own power transmission goes. If neighboring conductors are present the conditions may demand transposition in order to avoid mutual unbalancing influences or other inductive troubles. Where two three-phase circuits are carried upon one pole line or tower line, if it is desired to arrange each in an equilateral triangle, they may be so placed by using two long cross-arms. One circuit is strung each side of the pole, either one being arranged with the equilateral triangle base downward or base upward, as is desired. It is probably preferable to have the lines adjusted symmetrically in respect to the pole, as this will give more nearly balanced cross-arm stresses.

Very frequently, the triangles are arranged as two isosceles right triangles. In this case, one leg of the triangle is vertical, the other horizontal (along either upper or lower cross-arm) and the hypothenuse meets each arm at an angle of 45 degrees.

Again, a single three-phase circuit may be carried upon a pole line with all three conductors upon one cross-arm, i. e., arranged horizontally in respect to each other. While with the suspension link insulator the conductors of two circuits may be carried in vertical relationship from the ends of the three cross-arms, one circuit upon each side of the tower.

Wherever the arrangement of conductors is unsymmetrical either because of departure from the equilateral triangle or by the presence of two circuits in close proximity to each other, transposition of conductors is practised with a view to counterbalancing effects. The end sought is a *rotation* of conductors at certain specified distances along the line. If we speak of the three conductors as the *top*, *right* and *left* wires, one step in the transposition places the top wire at the right, the right wire at

the left, and the left wire at the top. This makes a *one-third rotation* and must be repeated twice more to complete the transposition. These three steps are equally spaced along the line and occur with a frequency sufficient to give complete transposition once in 1 to 10 miles, no well defined ideas of the needs being established. Each engineer settles the distance according to his own judgment.

If two circuits are used, both are treated alike in the matter, staggering the transpositions.

This one-third transposition may be established without interposition of extra poles; the length of span may be reduced to 20 or 30 feet; or, with normal span, an extra double pole may be used at the mid span, allowing for a one-sixth rotation to this point by bringing the left conductor to the top arm with the top conductor remaining there shifted to the right a little, the right conductor shifting part way to the left. The return to normal triangle with base down is made in the next half span, the one-third rotation being completed.

When the three conductors are arranged in one plane, this method of rotation cannot be accomplished between two successive poles, as the wires would cross. It is, hence, necessary to take two spans, the first shift putting the conductors into triangular relationship, the second shift going back to the original plane, but in rotated position of individual wires. This may be done without shortening either span from what it would have been otherwise.

The real necessity for frequent transposition is more noticeable in the maintenance of good telephone service along the right of way than in any other ways. Even in the one-plane arrangement of the lines the unbalancing due to non-transposition is not excessive for ordinary lines. The natural inference is that the precautions taken are more effective if they are located in the telephone circuit than if they are in the power circuit alone. Such is the case. A telephone circuit situated upon the same pole or tower as the power circuit should run about 10 feet below the latter or even more if convenient. Frequent transposition of telephone wires will even then be practised.

Another precaution that may be observed is to keep the telephone wires as close together as possible. If they are strung

upon a cross-arm the placing of a ground wire directly between them upon the same cross-arm will be effective.

The more nearly a line can be enclosed by a conducting system or network, the more effectively it is cut off from external disturbances. In order to protect a line from lightning, the use of grounded conductors is recommended. They should be of well galvanized or sherardized single-strand iron wire. Barbed wire is short lived. Two wires will afford more protection than one, and when used they are placed upon the ends of an upper cross-arm. The increased height of installation over that of the line conductors makes them more likely to receive the stroke of lightning. The farther to the side each wire is, the more successfully it will protect the circuit from accumulated charges caused by storms drifting across them.

When one grounded wire is desired for lightning protection its position should be above all other wires. It is best to run it at the pole top or tower top. It should then be grounded at every third or fourth pole, in the case of wooden construction, or at every pole with metallic towers. The latter will furnish, in themselves, the necessary grounds unless the anchor stubs are entirely surrounded by concrete. In case that the tower is not directly in contact with permanently moist earth, it may be supplied with artificial ground as in case of the wooden pole line.

A protective ground must be good compared to the insulation of the circuit which it is to protect. Hence, along the line the ground wire need not be supplied with elaborate grounding devices. Near the substations, power station, etc., where circuits enter machines the frames of which are grounded, these earth connections are more carefully made and their resistances kept low.

No one particular method of grounding has received universal preference. One method used is to bury a plate of copper or galvanized iron deeply enough to insure permanent moisture around it, connection being made to it by a grounding wire. Or 10 or 15 feet of the ground wire itself may be coiled in the bottom of the hole before setting the pole. An equally frequent practice is to drive one or more pipes into the soil, extending down into the moist earth. These grounds, have, however, rather higher resistances than is desirable in many respects. Moreover, the value

of the resistance varies quite largely. Pipes driven in as nearly identical conditions as possible will vary in resistance by several hundred per cent. The individual resistance of one pipe varies fully as greatly with change of seasons. The lowest conductivity may be expected in mid-winter when the ground is frozen. Sudden rises are characteristics of seasons of thawing or of heavy rainfalls. It would seem that with ordinary conditions the cycle passes through is a recurring one as long as the mechanical perfection of the setting is maintained.

When increased conductivity is desired over that of one pipe, other pipes may be driven and paralleled therewith. These pipes should not be close to each other, but separated by 10 or 15 feet. If grouped together, the contact area of iron to ground will be multiplied, of course, but the area of cross-section of conducting earth is not increased by the same factor and the multiple grounding is only partially effective.

In order to reduce the resistance variation above noted numerous expedients have been resorted to. Coke is buried around the plate or pipe in an attempt to enlarge the area of contact with the earth. Rock-salt is thrown into the earth used in tamping around the ground plate or into an enlarged hole around a driven pipe, which helps to retain moisture. Setting grounds in grassed plots is effective in increasing the conductivity.

As it is not possible to avoid crossings of transmission lines and public highways, railroads, telephone lines, or other transmission lines, extra precautions are sometimes demanded at these points in the nature of guards, etc. Where there may be danger only of a conductor falling from its insulating support and swinging loose, as upon a curve, guard hooks are frequently installed. These are simply curved iron hooks placed upon the end of the cross-arm and extending upward high enough to catch the wire if it is loosened from the insulator. A cradle of grounded iron wire and strap iron may be constructed directly underneath the high tension lines. If the telephone lines are above, this cradle may be placed to catch a telephone line before it falls across the power line. It is preferable to have the power line above the telephone line at a crossing, as only a few conductors are carried uppermost; the power lines are less liable to break than the telephone wires.

The cradle guard should extend well across the line, road, etc., to be guarded and at a height leaving plenty of head room for passing traffic—wagon or railway. Eighteen to twenty feet for wagon roads is none too much to count upon and twenty-five to thirty feet above the rails for railroad crossings. The de-

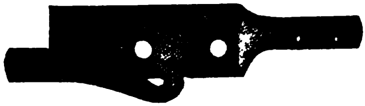


FIG. 110.—Safety line disconnector.

mands of other companies or corporations are sometimes fixed in this respect and compliance with their regulations required, both as regards clearance and length of span at crossing.

The cradles themselves may consist of wire spans supported by four sturdy, well-guyed poles. Between these wires are swung

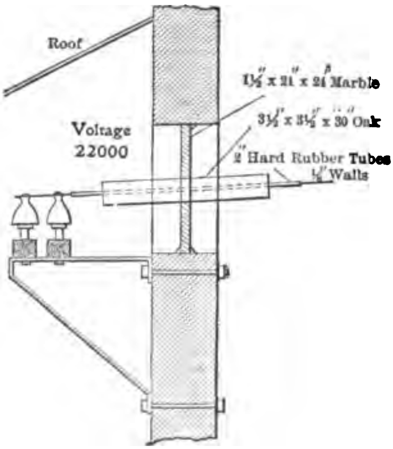


FIG. 111.—High-tension wall outlets.

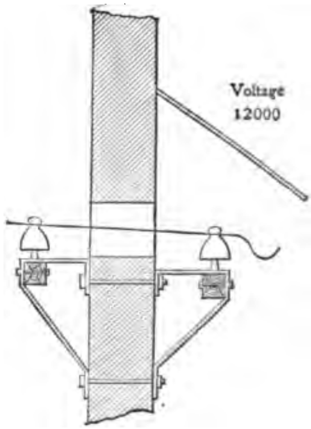


FIG. 112.—High-tension wall outlets.

cross pieces either of wire or metal straps tied together to maintain proper spacing.

The guard is sometimes reduced to merely three or four parallel wires strung from cross-arm to cross-arm of two poles, in a direction perpendicular to that of the power line.

The guards or cradles are usually grounded and contact with them by the live line grounds the conductor. If the guard is sufficiently high to allow plenty of room, dead grounding is not a requirement although it is always advisable.

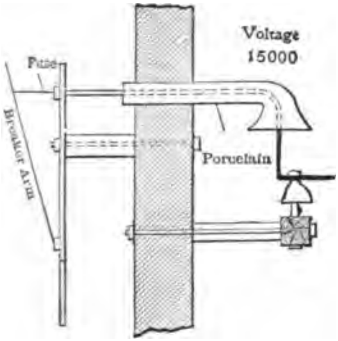


FIG. 113.—High-tension wall outlets.

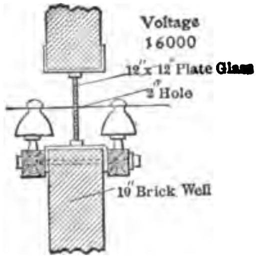


FIG. 114.—High-tension wall outlets.

Another method of securing safety from crosses, live wires, etc., is found by installing in each end of the dangerous span a safety disconnecting device. As long as the span is under tension the devices hold the wire tightly. If the conductor breaks at

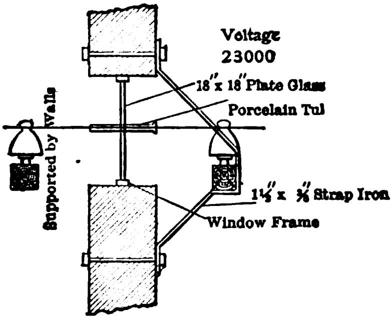


FIG. 115.—High-tension wall outlets.

any point in the span, the release from tension allows a spring to throw out the hook of the device and free the parts from each other. The devices at each end of the span act similarly wherever the break occurs and the dead conductor falls to earth,

leaving only short ends hanging at each pole. The affair is shown in Fig. 110.

High-tension Outlets.—In bringing high-tension lines into buildings, a great variety of designs are found. Many of these show points of great worth, though, evidently, some of them owe their successful operation to lack of severe or unusual conditions. Numerous illustrations taken from practice are given in the Trans. A. I. E. E. of 1904. Figs. 111 to 118 show some of these.

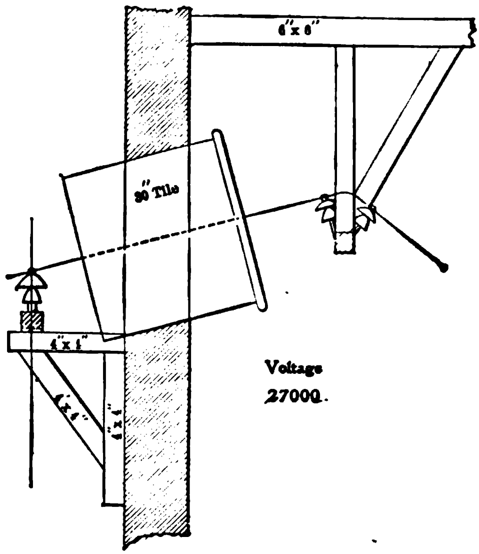


FIG. 116.—High-tension wall outlets.

In general, there are points of support for the line both inside and outside the entrance. If such is the case, the outer insulator and its cross-arm will generally take the strain of the first span. The wire then passes through the opening in the wall (*a*) with no protection (Figs. 112, 118); (*b*) through a glass or marble plate with or without a small enclosing tube (Figs. 111, 114, 115); or (*c*) through large tiles, with or without internal glass plate (Figs. 113, 116, 117). The outer insulator may be in the open or it may be protected by a special roof.

The weak points of these entrance constructions have proved

to be that wherever glass, porcelain, or other material closely surrounds the conductor, the collection of moisture, dirt, etc., thereon will lessen its effectiveness. Capacity effects between the conductor and enclosing tubes change the electrostatic stresses and in some cases hasten rupture. In all cases just cited, the insulators are the regular line insulators. The outer

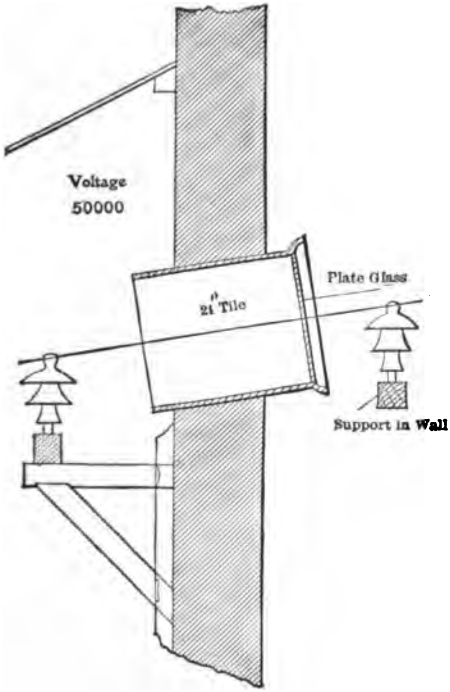


FIG. 117.—High-tension wall outlets.

one is not capable of taking very severe strains. The weather protection is not sufficient in most cases, Fig. 118 being by far the best in this matter.

For wall outlets which do not need to be closed on account of temperature conditions, it is probably better to leave a large opening through the wall. An outer housing, with or without a floor, will be built to keep out rain and snow. The conductor will be carried straight out through the opening, down through

the floor to a support and away to the pole. The high potential conductor of 40,000 volts or over *should be increased in size* in the section passing through the wall. This will, perhaps, necessitate the use of double insulators upon each side of the wall, allowing for a joint in the conductor between each pair. For very high voltages, the use of hollow conductors would be good practice in order to increase the surface, thereby decreasing surface tension and lowering losses and, at the same time, not wasting copper in the interior of a conductor of much too large cross-section.

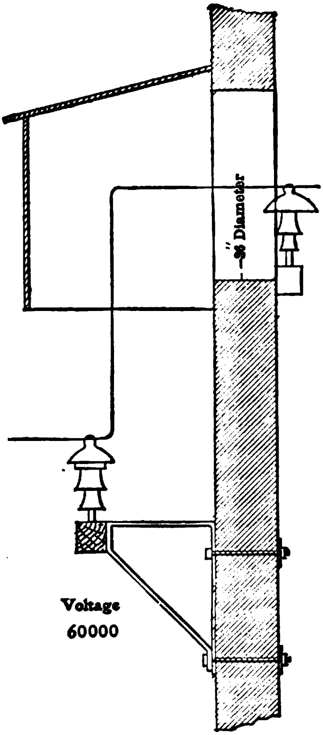


Fig. 118.—High-tension wall outlets.

Where the outer housing is not considered sufficient enclosure on account of severe weather conditions, multiple discs of glass or porcelain may be used to close the wall outlet. In this case the outer ones may have larger openings than the inner ones, the intermediate plates having medium sized holes. The outer plate will thus protect the next one without at the same time approaching too closely to the conductor. The inner disc is wholly protected. In the choice of material for this purpose, it must be remembered that glass is more hygroscopic than porcelain.

It is not necessary to have the outlets in the wall. In the most up-to-date construction the conductors are admitted through the roof or the cupola. The latter may be arranged much as in the case of a wall, the housing being an extension of the cupola roof and side walls.

A roof entrance is an excellent device. It is constructed self protecting as regards rain, etc. Two such are shown in Figs. 119 and 120. The first one is built up of several open-top petticoats with internal cylinders. It is made of porcelain and

weighs 180 pounds. Striking distance is 10 inches. Line potential is 66,000 volts. The other illustration is of a two-piece insulator with central bronze or copper rod. The insulator consists of a long bushing capped by an open-topped petticoat insulator. It is made of fibrous material.

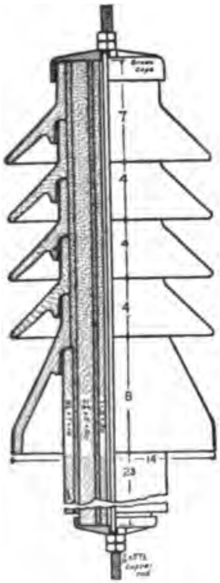


FIG. 119.—High-tension porcelain roof outlet.

FIG. 120.—High-tension fiber roof outlet.

Another variation of the roof entrance is made by using a large tile capped by special porcelain bushing with a series of petticoats.

The outdoor superstructure from which the conducting strand is led to the roof insulator may be built of wood or of structural steel. If it is wooden, precautions should be taken against fire risk. If it is metal, it should be effectively grounded.

CHAPTER V.

UNDERGROUND LINE CONSTRUCTION.

There are several faults in aerial line construction which can be remedied in part only. There are others which cannot be avoided while retaining this system. Sleet storms, already mentioned and illustrated in Fig. 54, are in the former class. Heavy windstorms are often very destructive, not only directly but indirectly by injuries the line may sustain from falling debris from trees, roofs, other lines, etc. These troubles are avoidable only to the extent that one is willing to add stability by increasing first cost.

Malicious interference, troubles caused by myriads of bugs, or by large birds belong to the unavoidable class. Probably the foremost objections to the presence of aerial lines in cities, however, are the three facts—pole lines are obstructions to traffic and to fire-fighting in congested portions of the city and they are universally unsightly in spite of all attempts to attain graceful curves in construction of the poles, arms, braces, etc. The further reality that generally no attempt is made to do more than establish mediocrity, except in cost, can leave no room for doubt of their undesirability. There would be less objection to them if it were possible to construct a line down one side of the street, with no guying, no cross-street connections, no service spans running at all angles. This end can be reached, in a measure, by making all service connections by underground leads, running them from the cross-arms to twisted cables inside a pipe attached to the pole, thence into the basement of the building served.

Underground Installation.—To do away with the whole aerial system is a very desirable thing in many particulars. So satisfactory is the result that, in many places, only subterranean construction is allowed. There is increased cost and also increased difficulty of maintenance or repair where faults do occur. Extensions to the system become costly. The building of an

open subway for stringing wires where they may be reached throughout their entire length is an expensive piece of business. Where the subway may be used for other service as well—steam-piping, freight traffic, passenger traffic, etc.—the expense may be justified.

Small combined installations are sometimes built in this way. A covered runway is built, walled with brick or concrete, having an arched roof. The dimensions may be anything from just large enough for the cables and pipes at the top with room for a man to crouch below and creep from opening to opening to a size where pipes may be suspended from the roof by stirrups with brackets upon each side wall for the support of cables, feeders, or mains, leaving room for inspectors and repairmen to attend to their duties without undue obstruction or inconvenience.

Protection to workmen requires that electric wiring in such tunnels be of insulated conductors. Abroad, a very small tunnel or trough is often used, being only large enough for the installation of the conductors at proper distances. A ditch is dug, usually under the sidewalk, and the concrete trough laid. Imbedded in the concrete are iron cross-pieces arranged to hold the pins for porcelain insulators. Bare wire is installed. The trough is then covered, a concrete slab being placed upon it. Earth to a depth of 24 inches or more covers the slab.

The Callender system of installing underground conductors provides a concrete bed of sufficient thickness to insure permanence, upon which cast iron or concrete troughs are laid. These individual troughs are large enough for several conductors or for only single cables as may be desired. With cast iron construction, however, the trough should contain all the conductors of one circuit (two or three as the case may be). With concrete troughs this is not necessary but it nevertheless is convenient. In the troughs are placed small bridges or supports for the conductors, upon which the cables are merely laid. They are surrounded by melted asphalt or other bituminous substance which hardens in place filling the entire trough and establishing a permanent insulation. The bitumen is fluid, however, and except for the bridging it would permit the conductor to sink slowly till it rested upon the floor of the duct. A cast iron cover (or a slab of concrete) is used for the top which is earth-covered.

This gives a solid construction of great durability. It is necessary in case of extensions to lay new ducts (Fig. 121).

FIG. 121. The Callender solid system in Bahia, Brazil.

The Edison system has been used a great deal, but is being installed now only in modified form. The conductors were

insulated from each other by ropes and the bundle slipped into an iron tube. The tube was filled with an insulating compound. Each tube length was a complete unit in the system. Coupling boxes were required at each junction and branches were arranged by three-way or four-way junction boxes. Where a general distribution occurred, there was used a special construction. A cylindrical distributing box was supplied with bus rings for connection to the mains. From these bus rings ran out the service lines, including positive, negative, and neutral and even *pressure wires* by which the voltage might be read.

The mains were laid directly in the soil about 30 inches below the surface. Service boxes were located at convenient intervals where service connections could easily be installed.

Where now used, this system is better fitted for the distributing or service section of the installation than it is for the main transmission of large amounts of power or of anything but low voltages.

Standard American practice of the day makes use of tubes or conduit into which the conductor is drawn after laying. One of these is a thin sheet-iron tube with a cement lining. This gives a smooth interior for drawing in the cable. The thin shell of iron does not last very long, but after its destruction the cement will remain as a protection.

An inversion of this type is that in which a thin tube of iron is surrounded by a bed of concrete. The number of such tubes installed may be varied, concrete walls between them being of a thickness about equal to the radius of the tube. The outer plank casing is frequently left upon the concrete as a mechanical protection against interference from workmen in digging ditches.

For several years, the most approved practice has been to use some form or other of clay conduit. Its life is such that no account need be taken of deterioration except from weakening of joints or destruction by accident or carelessness. The body of the conduit consists of well-burned clays, thoroughly vitrified and glazed. It is made in single-duct or multiple-duct form, as will be seen in Fig. 122, by means of which any combinations may be secured. Clay conduits were originally used only in the single-duct form. It is octagonal in shape, externally, with a circular opening. It is laid in such a way as to break joints,

successive layers resting directly upon former layers (Fig. 123.) A cement mortar binds the mass together. The individual joints are made, as in the case of multiple-duct conduit, by taping

FIG. 122.—Standard forms of clay conduit.

with burlap and cementing. A mandrel is inserted at the joint to insure alignment, and also to keep particles of cement from entering during construction. A later improvement of this type makes use of self-aligning units. This end is attained by manu-

FIG. 123.—Laying single-duct conduit.

facturing the two ends, the one with a projecting lip all the way around, the other with a corresponding cavity. With this, no mandrel is required, though it is generally used as a precaution;

the joint is more quickly completed and it is better aligned. This makes a smoother interior when handling the cable, a decided gain. The self-aligning conduit and the form of mandrel used with it are shown in Fig. 124. The mandrel is of wood and is 30 inches long, a section of conduit being 18 inches long. The mandrel has a special socket end for grasping the pull rod when the latter is extended through the last laid section of conduit to pull the mandrel forward. This forward pull will then clean out all foreign matter in the tube.

Whenever a number of ducts are required, it is cheaper, more expeditious, and more solid in construction, to use multiple

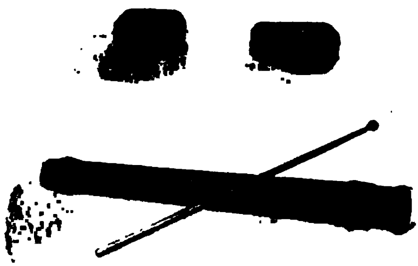


FIG. 124.—Self-centering conduit and mandrel.

ducts of two, three, four, six, or nine compartments, or combinations for the result desired. Two-duct and three-duct units are of standard length, 24 inches. Four, six, and nine-compartment conduits are 36 inches long. Special lengths are obtainable for use in breaking joints, entering manholes, etc.

Table XIX gives the manufacturer's data upon one group of conduits known as the Standard Vitrified Conduits.

The openings are round or square as desired, although the square opening is much to be preferred. There is less friction in drawing in the cable with a flat bottom opening. The cross-section of a square duct may be more nearly filled, as it is especially difficult to draw a second cable into a round duct because the tendency for the first cable to coil is so great. Even when a second can be drawn in the friction is much increased and may injure the sheathing or insulation. The entrance of a third cable would generally be absolutely impossible.

Table XIX.—Data on Standard Vitrified Conduit.

Style of conduit.	Dimension of square duct in inches.	Dimension of round duct in inches.	Outside dimensions of end section inches.	Reg. stock lengths in ins.	Short lengths in inches.	Approx. weight per duct ft.
2-duct multiple	3 3/8 sq.	3 1/4	5 x 9	24	6, 9 and 12	8 lbs.
3-duct multiple	3 3/8 sq.	3 1/4	5 x 13	24	6, 9 and 12	8 lbs.
4-duct multiple	3 3/8 sq.	3 1/4	9 x 9	36	6, 9 and 12	8 lbs.
6-duct multiple	3 3/8 sq.	3 1/4	9 x 13	36	6, 9 and 12	8 lbs.
9-duct multiple	3 3/8 sq.	3 1/4	13 x 13	36	6, 9 and 12	8 lbs.
Common single duct	....	3 3/8	5 x 5	18	6, 9 and 12	8 lbs.
Single duct self centering	....	3 3/8	5 x 5	18	6, 9 and 12	10 lbs.
Round single duct self centering	....	3 1/4	5 in. round	18	6, 9 and 12	10 lbs.

With square openings this spiral coiling is opposed by the shape of the walls. Not only, then, can the square hole be more nearly filled, but it is of a greater area of cross-section to start with for the same outer dimensions of the duct.

The trench dug for laying conduit should be of such depth that the completed installation may be covered with 24 inches of soil. They should be laid out in as nearly straight lines as possible and when finished are graded to street slopes if this allows a proper drainage toward the outlets. Any interference of other subterranean piping, as of gas, water, sewers, etc., should be avoided by preliminary design, when location of these are obtainable from city or operating company. Where this is impossible,

due to incomplete records, special construction or changes from the original grades will need to be made after work has developed far enough to furnish these data. Piping uncovered during construction should be braced and supported carefully to avoid injury and consequent damage claims. Depending upon the nature of the soil, shoring may be necessary to prevent caving in or pumping may be necessary to keep water from standing in the trench.

Where ditches interfere with traffic, crossings should be established of a substantial and safe character. These may be of a portable type, to be shifted from one place to another as desired. The foundation laid is best made of concrete. A 1 : 3 : 5 mixture

FIG. 125.—External key type of conduit.

of natural cement, sharp sand and gravel, or small-mesh broken stone is suitable for this purpose and should be laid in lengths of over 100 feet at one time. The bed should be 3 or 4 inches deep and of a width depending upon whether side concreting is to be used. If not, the foundation will be of the same width as the conduit. With side concrete, it should extend about 3 inches beyond the conduit line upon each side. This should be laid 24 hours before conduit is placed upon it.

The conduit is then laid, using short lengths at the start, in such a way that adjacent tiers break joints. When laid end to end the conduits should fit squarely and be in perfect alignment. The dowel pin holes or key ways must correspond to each other accurately. There are two ways of keying successive lengths into alignment. In one method there are dowel pin holes placed in the ends of conduits in the center walls. The other makes use of slots of square cross-section placed cornerwise in the external body just opposite each inner web or partition. These slots are open and one corner of the key used will extend to the surface of the tile. The construction can be seen in Fig. 125.

The latter type has certain advantages. A key may be easily

inserted in the external walls while difficulty is experienced in inserting it in a partition and putting in place the second conduit. In removing a broken section of a completed system for repairs, as may occur before the cable is drawn in, the dowel-pin type must be spread at the joint enough to permit sawing the pins or the section must be demolished with danger to adjacent sections. The new section cannot be held by dowel pins.

Fig. 126.—Laying multiple-duct conduit.

The external key type has a lug in each slot which keeps the key from entering one slot too far and leaving only an inch or so in the other section. This lug is easily removed by a light blow upon a chisel. The key is then slipped back into the slot, the other keys similarly manipulated, and the section is removed. A good section replaces it and the keys are slid forward into each end and holds as firmly as before.

When the conduits are thus assembled with pins or keys, a 6- or 8-inch strip of burlap having been placed under the joint

is wound around the joint to prevent any foreign material from entering, and a seal of cement mortar is applied. As the conduits are roughened near each end, the cement adheres and holds firmly. This makes the joint practically water-tight.

Retention of alignment depends, however, to a great extent upon these dowel pins or keys. It should be noted, therefore, by the

FIG. 127.—Laying multiple-duct conduit.

inspector or foreman that two are inserted at each joint. The omission of the pin will greatly facilitate work of laying and a constant watch is necessary to insure proper insertion, especially where some effort is required or trouble experienced in placing them.

Successive layers of conduit are laid at the same time (Figs. 126 and 127) it not being advisable to wait for lower layers to set before putting on the upper layers. The cement mortar applied to each joint is not sufficient to lend much strength to the joint. Consequently, if it is allowed to harden and is then disturbed

by the placing of more conduit, it will be cracked or loosened and will fail to exclude moisture. When the conduits are in place, the side walls of concrete are tamped in, great care being taken to avoid displacing the conduits in either direction. These walls should be at least 3 inches thick. It is not universal practice to use the complete shell of concrete. Frequently the side walls are omitted, simply laying the foundation bed and adding a top layer after the conduit is in place. In this case, the earth filled in at the sides must be very carefully tamped. It should be put in before the concrete topping is laid. Whether side walls are used or not, there should be this top dressing or concrete slab

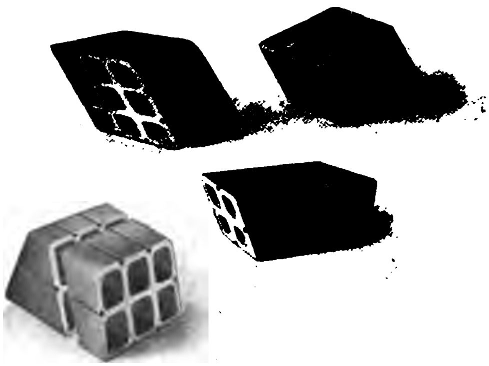


FIG. 128.—Sections of radial conduit.

of about 3 inches thickness to extend to the edges of the walls in the one case, or of the conduit in the other case. It is from the upper surface of this cap that one should measure in allowing for the 24-inch filling of earth.

While curves are to be shunned, especially if of short radius, there may occur instances where they are unavoidable even by changing the grade for a considerable distance back from the obstruction met. In such cases, the regular conduit construction is slightly flexible. In laying successive lengths, there may be a small bend made at each joint. Where this is not quite sufficient special conduits are available of various lengths, cut at different angles. A few such are shown in Fig. 128.

Sometimes curves may be avoided by the installation of a manhole at the point in question.

There are fiber conduits on the market also. Some of them are especially fitted for particular service. In selecting from these for regular conduit work there are several things to consider. No fiber can compete with clay in respect to insulation qualities, fire resistance, life, etc. But, generally speaking, fiber can attain very high values in these points and, in turn, out-point clay conduit in other matters, as weight, jointing, curves, etc. This makes the use of fiber permissible.

Table XX.—Orangeburg Fiber Conduit Dimensions and Weights.

Inside diameter inches.	Type of conduit.	Length in feet.	Thickness of wall in inches.	Approximate average weight per foot in pounds.	Feet per 100 pounds	Approximate shipping wt. in pounds per 100 feet in L. C. lots crated.
*1	Socket joint	2 1/2	1/4	0.38	264	75
1 1/2	Socket joint	5	1/4	0.70	142	110
2	Socket joint	5	1/4	0.85	117	130
2 1/2	Socket joint	5	1/4	1.02	98	50
3	Socket joint	5	1/4	1.20	83	170
3 1/2	Socket joint	5	1/4	1.45	69	205
4	Socket joint	5	1/4	1.62	62	240
1	Sleeve joint	2 1/2	1/4	0.40	250	80
1 1/2	Sleeve joint	5	1/4	0.74	135	115
2	Sleeve joint	5	1/4	0.90	111	140
2 1/2	Sleeve joint	5	1/4	1.10	91	160
3	Sleeve joint	5	1/4	1.30	77	180
3 1/2	Sleeve joint	5	7/16	2.50	40	325
4	Sleeve joint	5	1/2	3.20	31	455
*1 1/2	Screw joint	5	5/16	0.85	117	140
*2	Screw joint	5	3/8	1.32	75	175
*2 1/2	Screw joint	5	3/8	1.65	60	220
3	Screw joint	5	7/16	2.20	45	275
3 1/2	Screw joint	5	7/16	2.50	40	325
4	Screw joint	5	1/2	3.20	31	455
2	"Linaduct"	5	1/8	0.55	180	85
*2 1/2	"Linaduct"	5	1/8	0.65	153	95
3	"Linaduct"	5	1/8	0.75	133	110
3 1/2	"Linaduct"	5	1/8	0.85	117	140

* Made on order only.

Fiber conduit is made in various sizes, from 1 inch diameter to 4 inches diameter. The duct is cylindrical and the walls are

from 0.125 to 0.5 inches thick, depending upon the method to be employed in installing it. Because of this thickness of shell, and its intrinsic lightness, it is made in 5-foot lengths for standard work, except in the case of the very smallest sizes which are 25 feet long. Data are found in Table XX. There are three types of joints used in the heavier conduits, socket joint, sleeve joint, and screw joint (see Fig. 129). The socket joint is 0.375 inch long and is made by inserting in the turned socket of one conduit

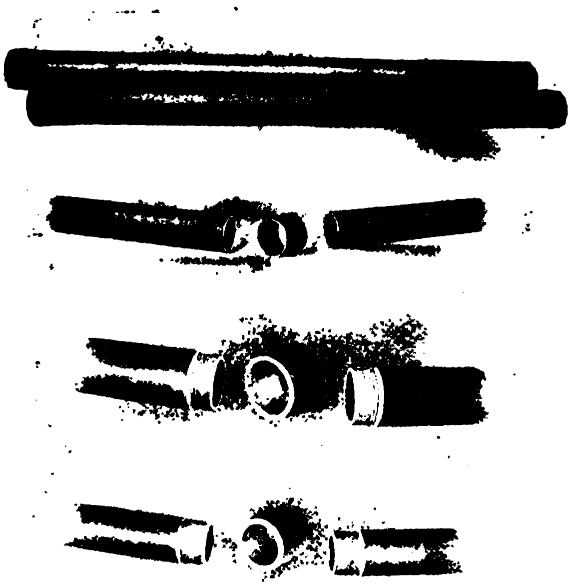


FIG. 129.—Types of fiber conduit.

the correspondingly turned tongue of the other conduit. This length of overlap is sufficient for exclusion of mortar, dirt, etc., and gives a fairly water-tight joint. It is generally laid upon a 3-inch bed of concrete. Parallel ducts of the same layer are spaced at 0.25 to 0.5 inch, being separated by the wooden teeth of a comb-shaped rack (see Fig. 130). Upon this and between the ducts is laid a concrete filling to a depth of about 0.5 inch. The stone used in this concrete must be small in order to allow for properly working it into the interstices. Gravel is very

satisfactory. The successive layers are then added, being laid in exactly the same manner. Topping the upper tier will be a concrete layer about 3 inches deep to serve as a guard against the pick and shovel in case of later excavations. No special lengths of the straight conduit are manufactured. This is not necessary because of the ease of cutting to measure wherever such lengths

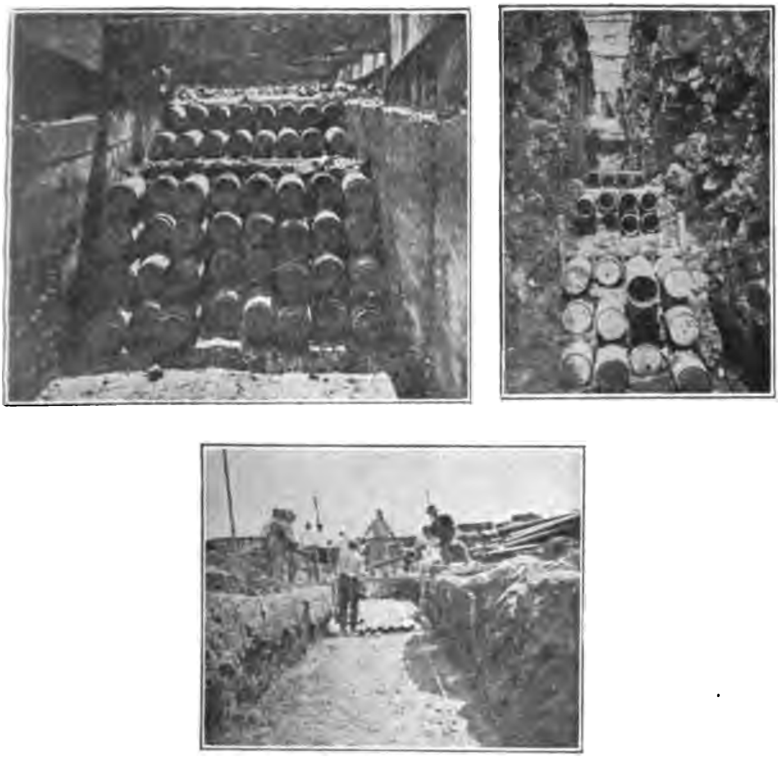


FIG. 130.—Laying fiber conduit.

are required. A small, special, hand-power lathe is used for this purpose, the cutting and the turning and fitting of the new joint being all accomplished in a few minutes' time. Instead of turning a new joint upon the cut ends, a sleeve joint may be used.

This sleeve joint is also used for regular work. The conduit ends meet squarely, a collar or sleeve having been slipped over

one section is advanced to cover the joint. The sleeve is 3 inches long, a 1.5-inch lap upon each section being considered sufficient for all purposes. This type is laid similarly to the socket type.

A screw joint is made for use either with or without concrete envelope. This conduit is a little thicker walled than are the others owing to the depth required for cutting threads. The joining is done by a threaded collar into which both sections are screwed by hand. A liquid compound is applied to the threads before inserting which hardens and seals the joint.

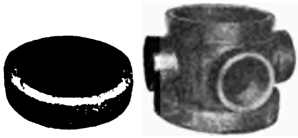


FIG. 131.—Fiber junction box.

A conduit of thickness reduced to 0.125 inches has been given the trade name of *Linaduct*. As its name implies, it is always used for lining concrete ducts and is embedded in much the same manner as is the sleeve type.

T-joints, crosses, caps, reducers, etc., are available for construction, as are also two-way, three-way, and four-way junction boxes or service boxes about 8 inches high and having a chamber of about 8 inches diameter (Fig. 131).

The interior of fiber conduit is especially smooth and regular. No offsets can occur at the joints and no concrete can enter. The material is tough, strong, and durable. It is incapable of maintaining combustion, continuing to burn only in an electric arc. Remaining 192 hours in water, the weight increased by about 4 per cent. Its low absorption taken together with its chemical stability in the presence of acids, alkalies, etc., will give the conduit long life in underground work. In the high potential test a regular section of 0.25 inch thickness punctured at a little less than 30,000 volts when dry and at about 23,000 when soaked in water for 48 hours.

Compared with other conduits, fiber is much the lightest and most easily and expeditiously handled. Freight and haulage are therefore low per duct foot. The conduit is quickly and securely laid, no wrapping of joints being necessary, and work

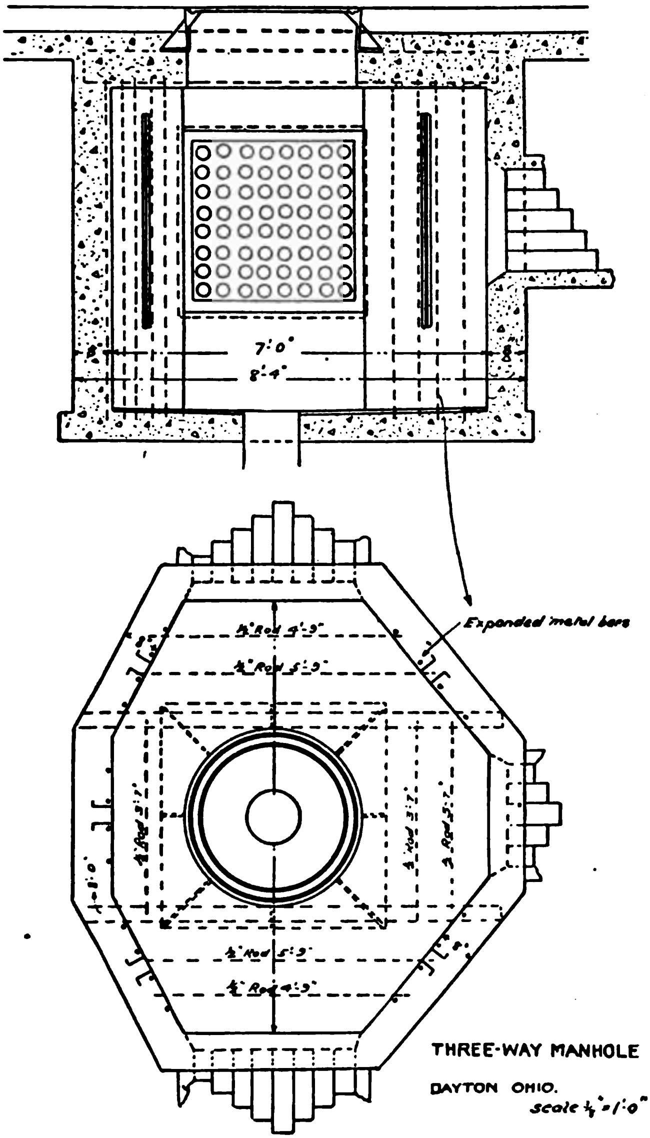


Fig. 132.—Concrete manhole.

progresses rapidly. Breakage is reduced to a minimum, being, upon an average, less than 1 per cent. Broken or crushed sections may be cut and the undamaged parts utilized. The space occupied by this type is somewhat less than for clay and there is a saving in excavation.

Manholes should be established at intervals of about 300 feet. This corresponds to a city block in many localities and is departed from in either direction in order to place manholes at streets intersections. With long blocks or crooked streets, an extra opening at the middle of the block is advisable. They are constructed of brick and concrete, or reinforced concrete alone. They should be 5 to 8 feet deep and with sides 4 to 6 feet high before arching. They may be square, oblong, octagonal, or oval, as best suits the situation. Square corners are hard to turn properly with cables, however, so the other shapes are most frequent. A good concrete construction is shown in Fig. 132 for three-way service. This illustration is taken from a publication of the H. B. Camp Company. The concrete floor should be at least 6 inches thick. The walls are 8 inches thick. The main inside dimensions are 7 and 8 feet. The general shape is a distorted octagon. The floor is laid so as to drain toward the center, where a screened opening in the floor is left. This will be occupied by a sewer connection. A back trap should be inserted in the drain pipe to prevent overflows from the sewer.

At the cable entrance the concrete walls should be rounded off to prevent abrasion of the armor or insulation in passing it over sharp corners.

The roof is flat, being supported by I-beams or channel beams. An arched roof is wasteful of space and requires deeper setting of the floor in order to obtain the same wall space. The thickness of the roof will be 10 to 14 inches, depending upon the dimensions of the chamber.

If desired, with the use of I-beams, arch blocks may be used in roofing. These do not rise high enough to cause any difficulty. They are of hollow tile, are light, strong, and quickly placed.

Cast iron covers upon a cast iron frame set in the concrete roof will close the manhole. This cover is at street level and takes directly the weight of traffic over it. The opening is about 30 inches in diameter. If a two-way manhole is desired, the

above design could be narrowed down making it symmetrical to a center line, each half being like the left hand part of the figure. For a four-way connection, it would probably be widened, each half partaking of the nature of the right hand half, or even becoming a regular octagon.

With brick walls it is preferable to use a vitrified glazed brick. The walls should be 12 inches thick and carefully laid. The floor and the roof will be laid in much the same manner as before described, as they are of concrete. The outside of the walls should be plastered with a good cement mortar.

As soon as the construction is complete, the ducts should be *rodded.* This consists of inserting jointed rods, connecting it section by section (see Fig. 133), and pushing it through from one

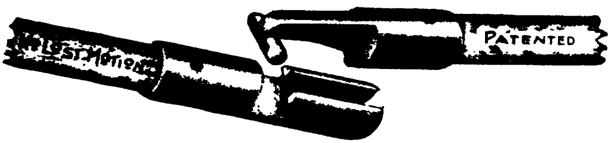


FIG. 133.—Conduit rod coupling.

manhole to the next. A wire or rope is attached to the end of the rod and pulled through to the second manhole, the successive sections of rod being disconnected as they are pulled out of the duct. Then a wooden mandrel is drawn through. It is about a foot long and is slightly smaller than the duct opening. This is done to insure an opening of full cross-section throughout and aid in removing any possible particles of concrete, stone, etc. It is sometimes followed by a steel brush.

Attached to the last cleaning instrument used is a long steel wire which is left in place in the duct for the purpose of pulling in the conductor when it is to be installed.

This rodding is done by the contractor, as it is his test of freedom of the duct. It should not be delayed till installation of cable is desired, as any obstruction will mean delay of work. It should be done after each section is complete from one manhole to the next, including covering. This will show whether or not the tamping of earth or concrete about the conduit has displaced any of the sections and broken the joints. With multiple duct conduit the satisfactory passage of mandrel in one or two

ducts of each tier is not enough. Each duct must be rodded, anyway, in order to put in the drawing-in wire and it should be given the same clearance test as the first duct is given.

Interior construction of the manhole varies from elaborate provisions for carrying the cable to none whatever. Side brackets are sometimes attached to the walls and support cable racks. A simple and sturdy form of these is shown in Fig. 134. They may be obtained with spacings between racks of 6 or 8

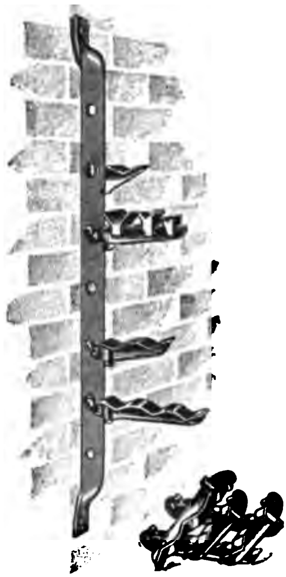


Fig. 134.—The Cope cable rack.

inches, and spacings between cable centers of 3 or 4.5 inches. They will support from 500 pounds to 1000 pounds each.

The weakest point in the high potential underground system is the manhole. The cables are insulated, lead covered, and isolated in the conduit ducts. But, upon entering the manhole, they are massed about the walls, carried upon racks or insulators, and are in dangerous proximity to each other if trouble once occurs. The result often is that, as soon as the arc starts, in such a location, all of the cables passing to the manhole are affected, being grounded or perhaps destroyed.

A more recent development which is useful in such installations makes use of a special terminal conduit for the manhole entrance. It is flaring in shape with much thicker walls and partitions at the open end. This serves to separate the cables somewhat from each other. The conduits themselves may be separated, further increasing the distances between cables. Figure 135 shows the idea of this, as well as illustrating the special terminal conduit. To complete this construction, slate shelves

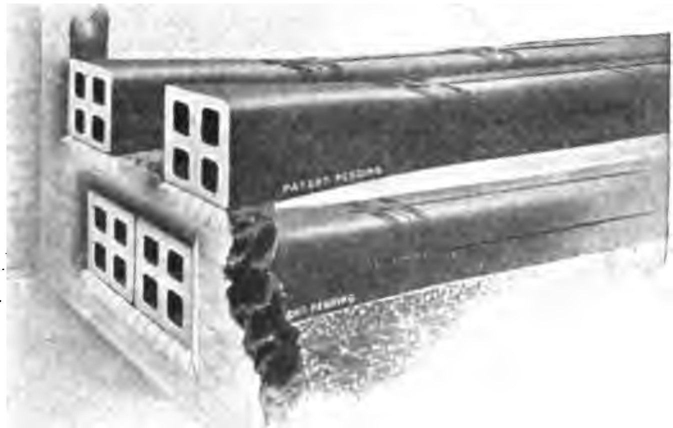


FIG. 135.—Entering a manhole.

may be placed around the entire wall upon the level with each duct. The cables coming out upon these shelves are bent to one side and are wholly supported by them. Figure 136 shows how the shelves separate successive layers of cables from each other.

When it is desired to further protect from each other adjacent cables upon the same shelf, a very flexible and handy construction is provided for by the use of short length single duct conduit (vertebræ) split for assembling. The lower halves are placed first by simply lifting the cable and slipping the half vertebra into place. The upper ones are then put on as a capping. They are

of the self-centering type so that successive sections hold alignment and the whole cable is protected. Moreover, the longitudinal splitting of each vertebra is accomplished in such a way that the two faces of each piece are not in the same plane and the upper half seats firmly upon the lower half. The details of these vertebræ and their assembly and use are shown in Figs. 137 and 138.

When the Edison tubes are used, the service lines may be taken off at intermediate points along the line. In fact, wher-

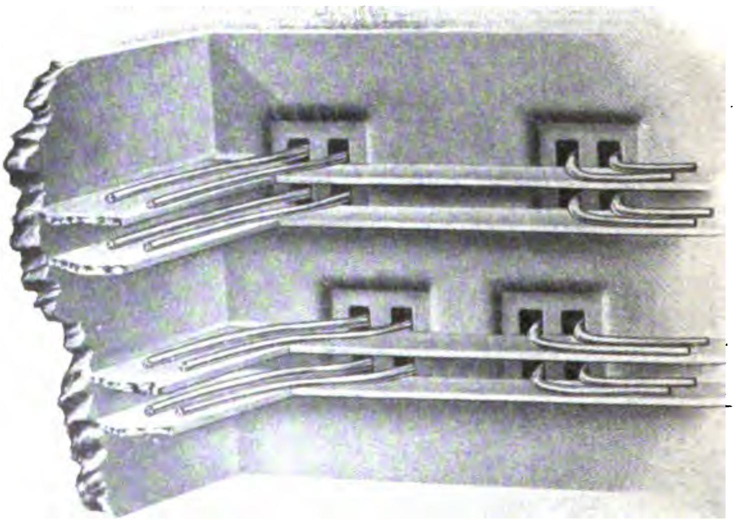


FIG. 136.—Cable support in manholes.

ever a junction box is necessary—that is, at any joint—a service box may take its place and leads go therefrom to the customer. When clay conduits or fiber tubes are used, this is not an economical way of installing.

In the latter case, service mains are run from the manholes through service ducts of single tube conduit. These conduits are laid as an upper layer upon the regular conduit, if desired.

They lead to service boxes along the line between manholes, and from these points the customer's leads are taken. Boxes are spaced at from 100 to 200 feet.

The service boxes are, in a sense, small manholes. They are constructed in much the same manner, but are only about 3 feet square and deep enough to reach the bottom of the service conduit. Three-inch flooring and 6-inch walls are sufficient. The same precautions must be taken against entrance of water through walls as are practised in manhole construction. In

FIG. 137.—Details of vertebral conduit.

draining, however, the floor is level with the duct and hence, with a proper slope, the service boxes and the ducts also will empty into the manholes, which, in turn, drain into the sewer, as before indicated.

Ventilation of all subterranean passages and openings is necessary. Workmen cannot remain in the manholes, if good air is not provided. But even when work is not in progress, precautions of some nature must be taken or there will be a gradual accumulation of gas in the chambers from leakage of gas mains and sewers through the surrounding earth. When such an accumulation has occurred, a destructive explosion is imminent. The gas may be fired by arcs between cables, electrostatic sparks, a workman's lantern, a lighted pipe, or any one of many possibilities. The destructive effects sometimes are well nigh incredible.

This ventilation may be accomplished by means of natural draft provided by sloping the conduit between manholes and leaving open vents in the manhole cover. A more reliable method is to force ventilation, although this is not always necessary. By sealing the manholes by double covers and forcing air into the passages, a pressure slightly above atmospheric pressure may be maintained without great loss. This establishes an *outward* pressure which overcomes the tendency toward gas accumulation.

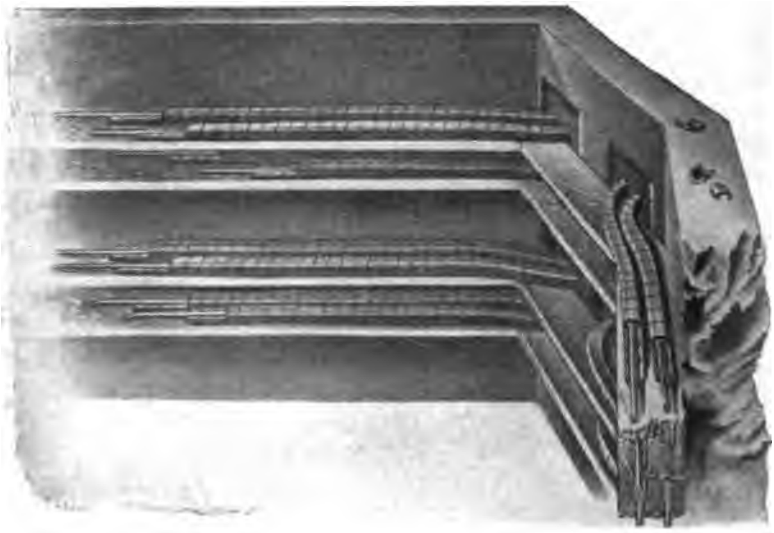


FIG. 138.—Installation of vertebral conduit.

Drawing-in the cable is a step in the construction where much damage may be done without immediately recognizing it.

The cable ways must be smooth and regular, with no burrs or blisters upon the conduit, no concrete lumps projecting inwardly at the joints, no sharp turns or bends, no offsets.

The presence of these faults will prove injurious to the lead sheathing of the cable by scratching it or marring it and lowering its value as a protection against moisture absorption by the insulation. By far the majority of breakdowns of cables can be laid to this cause. The sheathing may be injured even before

entering the duct by incautious handling as it is lead into the manhole.

When ready to install the conductor, the spool upon which it is wound should be mounted upon an axle in such a position above the manhole that the cable leaving the spool will descend without much bending into the manhole. Here it should be passed around a large drum of sufficient radius to avoid straining the lead sheathing or the insulation. From this it will enter the duct where a workman must guard it from injury by abrasion. The rope or wire left in the duct for this step is attached to the end of the cable and they are gradually pulled through the duct. The drawing-in rope is wound upon a windlass drum, the force being exerted by workmen. This is more easily and quickly controlled in case of accident than if horse-power is used. The windlass is placed in or above the second manhole and the ducts are thus filled successively.

If it is desired to place two cables in the duct, a second leading in rope should accompany the first cable into the passage to do duty after the removal of the original rope.

Electrolysis.—Underground cables drawn into any conduits are always lead covered, because this metal is not chemically a very active substance. So far as chemical corrosion goes, it is therefore quite satisfactory. It is easily injured by electrolysis, however. If stray currents from railway lines are present in the earth immediately surrounding the duct, or if induced currents are found there, at whatever points the lead cable sheath is grounded, there may be currents entering or leaving the metal for the earth. These grounds may be due to moisture in the conduits at the joint, broken conduit walls, foreign matter in the duct, etc. The passage of such a current into the metal and its acting as a conductor cause no injury whatever. But at a later point the current must again leave the sheathing and here the lead is attacked and is carried away. Continued action of this nature will render the lead covering of no value, the insulation will deteriorate and the conductor will become grounded.

Contractor's Duties.—Contracts for the laying of an underground system usually state that right of way is to be secured by the company while the contractor will obtain whatever other permits are necessary. The contractor will furnish all materials

except conduits, manhole and service box castings, and racks or shelving, I- or channel-beams. His responsibility should cover proper street guards, bridges, repaving, quality of materials, street obstructions at fire hydrants in drainage, etc., damage to materials or to outside parties and property. His work should be definitely stated in detail and he should give bond.

The engineer for the company directs the order of the work, the location of the system, manholes, service boxes, etc. He inspects material, passes judgment upon workmanship, celerity of work, and any alterations found to be necessary. His authority is to be recognized by the contractor.

CHAPTER VI.

SWITCHBOARDS AND PROTECTIVE DEVICES.

Switchboards.—The evolution of present electrical engineering practice is nowhere more strikingly exemplified than it is in the development of the modern switchboard.

No thought was given to controlling devices or protecting devices until the matter was thrust upon the engineer. The first installations consisting of small low voltage units used for distribution of current to short distances demanded only little in this direction. Generators placed near the walls were wired as simply as possible. The leads would run to walls or ceiling and were carried upon glass or porcelain knobs. The switch in the main line might be upon the frame of the machine itself (Edison bipolars). A line switch might be placed upon the wall, being a second switch in the series or being the only one in the line. Field switches were similarly placed. The wiring was open and ran as directly as possible. Where meters were installed, they were grouped upon the wall with the switches.

As machines increased in size and in numbers, the massing of suitable switches and instruments upon a wall became very troublesome. Conductors had to be carried under and over other conductors. They looped about instruments or passed them in close proximity. They interfered with each other and with the switches, etc. Meter readings were erratic and unreliable. Partial relief from these troubles was afforded by moving the supporting frame or wall out from the wall of the building. A special wooden panel was constructed allowing the wiring to be done in its rear. Wires passed to the switches between the slats of the frame-work and no holes were needed for the conductors. All machines installed were isolated, no paralleling of generators being practised. Each unit, then, consisted of a self-excited generator demanding certain switches, or a separately-excited generator where generator and exciter were independent of all other generators and exciters and demanding their individual switches.

The rack switchboard has been extensively used, but in later practice this skeleton form has been abandoned for the original solid panels with drilled holes for conductors. The wooden construction, which in time became very ornate, gave way to the use of other materials not combustible. Slate, marble, etc., were used and remain the foundation for supporting of switches today. Large slabs of the slate or marble were cut and fitted together. Frames surrounded the whole and holes were drilled wherever it was desired to mount instruments, etc. They were bulky, inconvenient, and inelastic.

FIG. 139.—Typical alternating-current switchboard section.

Still further progress has brought into use the panelled slate or marble board supported upon angle iron framework or iron pipe framework. As satisfactory construction as any for general work may be taken as slate body with "marine" (oil) finish, a dull black surface, the framework being made of iron piping. This gives a finish which is easily maintained in proper condition and is equally easily matched for extensions. It is a good color and lends itself well to the general effect obtained with the assembly of instruments, switches, etc. There is no glare of reflected high lights in the eyes of the operator or attendant. The use of iron pipe frame insures ease of assembly, as there are no bolt holes to be accurately placed, etc. Low cost is attainable and rigidity is not sacrificed. The yoke fittings allow accurate adjustment and also flexibility or ease of alteration, if it becomes necessary. A typi-

cal alternating-current panel is shown in Fig. 139 and a modern railway board is illustrated in Fig. 140. Another departure, called the *benchboard*, is that shown in Fig. 141. A board is sometimes broken up into separate sections with apparatus installed upon posts or *pedestals*. It is then called a *pedestal board*.

The introduction of the practice of paralleling machines, grouping them upon common bus bars, the demand for interchangeability in operation of generators or of exciters, the use of protecting devices in the circuits, all tended toward the standardization of switchboard practice. Despite the difficulties, this

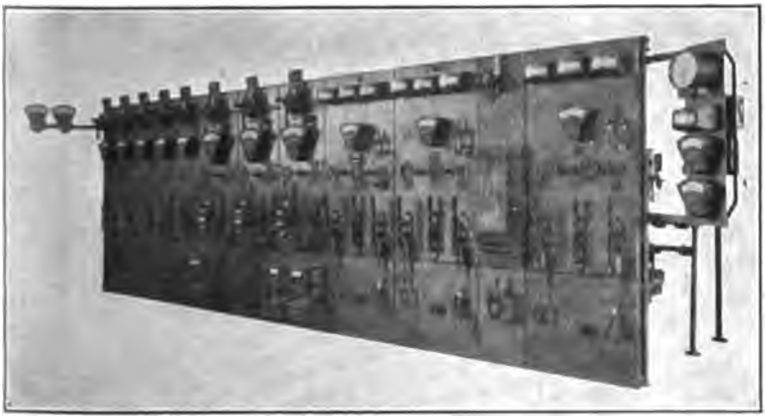


FIG. 140.—Modern railway switchboard.

tendency has produced very decided results and current practice can be divided into two classes. The first of these is the *direct control switchboard*, in which the switches, rheostats, etc., etc., are all controlled by hand from the single switchboard consisting of assembled units. The second class is the *remote control switchboard*. As its name implies, all main circuit apparatus is displaced from the switchboard to varied distances and is controlled mechanically by levers, rods, gears, etc., pneumatically by compressed air stored in tanks or electrically by motors, solenoid coils, relays, etc., operated by low voltage circuits. In both types, certain standard dimensions have been adopted, the board being divided by vertical lines into *panels* and the panels by

horizontal lines into two or three parts. Manufacturers have thus been enabled to arrive at the beginning of standardization. Owing to the unending variety of conditions of station lines and service, to say nothing of individual preferences of engineers,

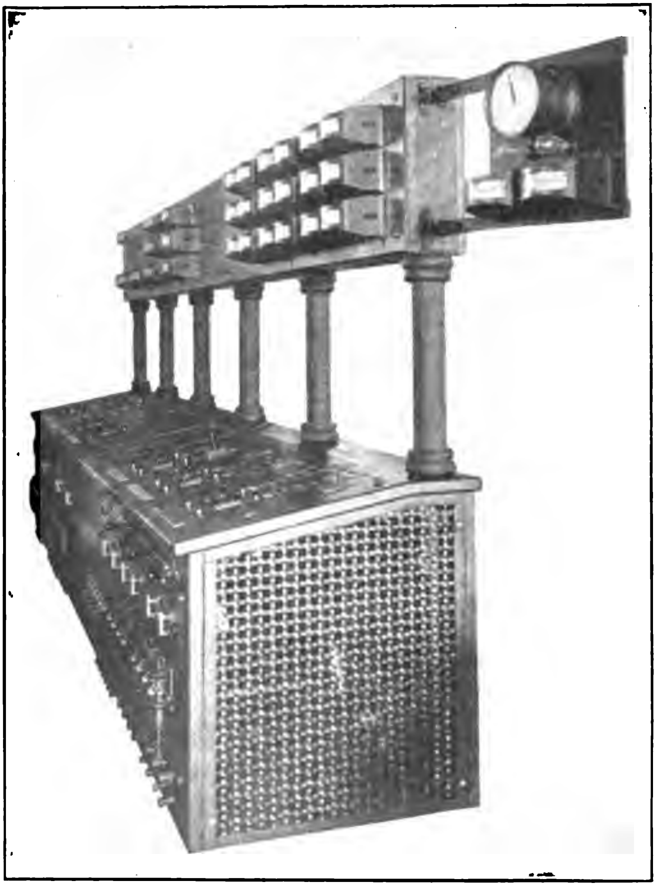


FIG. 141.—Benchboard.

switchboard practice cannot be standardized in the same sense as can other features of engineering construction. In all cases, however, the detail of its construction should be worked out before the station plan is fixed upon, in order that due account

may be taken of any ducts, passages, chambers, etc., to be placed under the floor, supports and braces running to floor and walls, spacing of floor beams, design of foundation supports, and accommodation of all devices used.

Choice of type of control will necessitate striking a balance between high cost upon the one hand and inconveniences and risk of injury upon the other hand. Some of these refinements and devices have become absolutely essential in the important work of today, where, a few years ago, they were considered as optional if not superfluous. This is due to increased bulk of power handled, increased intricacy of circuits, etc.

The simplest conditions met in transmission of power is the case of the single generator-single line. They may be single phase, two phase, three phase, or direct current. The switchboard for this service will consist of a single panel with switches thereon as well as meters or apparatus controlling these devices. This is known as a *unit type* of control, for to a given generator corresponds a given line. When a transformer is interposed between the two, the type is still *unit*. With increased number of such installations, this construction may be duplicated for each, and panel after panel added to the switchboard to accommodate them. The increase in number of machines, if they are run wholly independently, will not increase the reliability of any one line. The service is just as subject to interruptions as it was before. Consequently, the units are generally tied together by leading to certain points common to the like circuits. These are known as *bus bars* (from *omnibus*). They consist of heavy conductors or heavy bars, generally of copper carried upon insulated supports and being of sufficient length to accommodate all connections and to avoid long connecting leads. When installed behind the switchboard, they reach the full length thereof. There are two places for making this parallel connection, namely, between the generator and the transformer (low voltage bus bar), and between the transformer and the line (high voltage bus bar). Bus bars are used in other parts of station wiring also to simplify and aid in transferring and to connect equalizer leads. These are called transfer buses and equalizer buses.

The types of switches available for this work are innumerable, but they may be classed as plain *disconnecting switches*, opening

under no load, and *circuit breakers*, opening under load. They are *air break* and *oil break*, either type being *non-automatic* or *automatic.* The automatic as desired will act instantaneously, after a definite time has elapsed, or, being set for a certain time limit, its action will require a time inversely proportional to the demand made upon its carrying capacity. In regard to the time element required these are known as *instantaneous*, *time* and *inverse time.* This time limiting is preferably introduced through relays. All switches which open automatically under load, including both air break and oil break, are called circuit breakers.

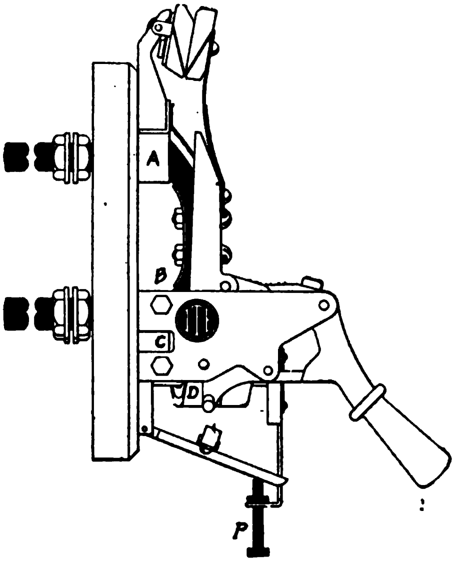


Fig. 142.—I-T-E circuit breaker.

The simplest switch is the knife blade switch in which the blade engages between two clips. This draws an arc between copper clips and switch blade and injures each if a large current is slowly broken. To avoid this, *quick-breaking switches* are designed for the lower currents and circuits of low inductance and *carbon-break switches* for heavier currents. In the latter, the last point of contact occurs between two carbon blocks An arc will not be long maintained there. When copper contacts must be of large area the multiple knife blade switch frequently gives place

to the laminated end-bearing switch in which the blade is constructed like a laminated brush and is bent so that the ends seat upon two flat copper faces. Owing to the magnitude of the current carried by these, they are generally of the automatic type. The general principle of this scheme is quite well shown also by Fig. 142 of the I-T-E circuit breaker. The laminated bridge, *B*, rests upon contact plates *A* and *C*. Above *A*, are shown two contact points paralleling the main contact, the upper one being carbon-faced and opening last. The trip coil shows at *D* and adjustment is made at *P*.

Fig. 143.—Three-pole alternating-current oil switch, with overload and low-voltage release.

A later type of breaker made by the General Electric Company, for use on direct current or alternating current circuits is of the general type shown in Fig. 143. The particular form shown is a triple-pole breaker with automatic release for low voltage as well as for overload.

Any automatic devices are available, including low voltage release, high voltage release, overload trip and no load trip.

The low voltage release is operated by a potential or shunt coil, while the overload or underload protection is secured by the use of current or series coil. The main features of this circuit breaker in its varied forms are a laminated brush with end contact for the main circuit and the first opening; special infusible metal terminals easily replaced for a secondary opening; carbon terminals for a third and last opening.

When, upon the air-break switch or circuit breaker, there have been placed terminals of a material not easily affected by the arc

drawn and not conducive to the maintenance of an arc, and when a magnetizing coil has been arranged to blow out this arc, little more can be done to aid in its interruption of the circuit. The result is that for high voltages, long arcs are drawn and the opening of the circuit is not positive and prompt. By interposing between the switch terminals some suitable fluid heavier than air, additional effectiveness is attained. The most suitable substance found is oil. This is the *raison d'etre* for the oil break switch or circuit breaker.

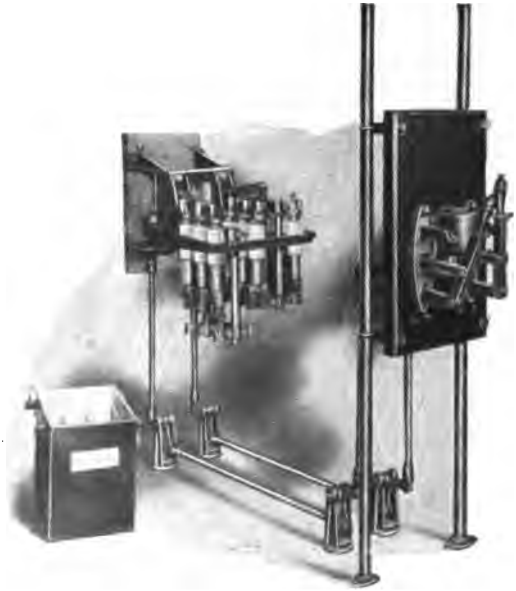


Fig. 144.—Triple-pole, double-throw oil switch, remote control, overload release.

The oil switch is built in sizes ranging from those used for 50 amperes at 600 volts to those used upon the largest power lines of highest commercial voltages. In the low voltage types, the single- double- or triple-pole switch dips into a metal tank filled with oil. The tank may be divided into compartments by the use of insulating material as partitions. This will avoid short-circuiting arcs under the oil.

In the larger sizes there are separate compartments or tanks for the different poles of the two-pole or three-pole switch.

These are even separated by brick walls and thus practically isolated.

They are mounted upon the back of the switchboard only in the smallest capacities, in which case they are hand operated by levers attached to them through the board. Owing to the need for economy of room the medium sizes and large sizes are displaced by at least short distances from the board and are operated by various means. Figure 144 shows a triple-pole, double-throw breaker for remote control in which the motion is transmitted from lever to switch by rods and bell-cranks. The switch

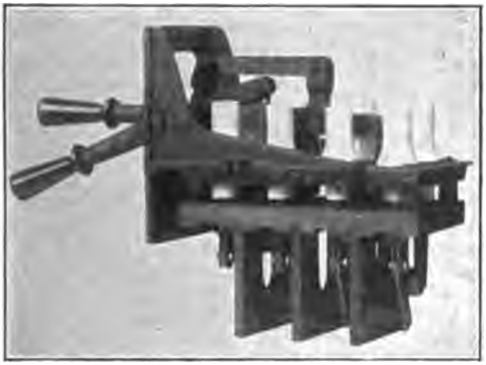


FIG. 145.—Small hand-control oil switch.

may be hung upon the wall or upon a second framework similar to that for the switchboard itself. It may be placed upon the floor, in a vault under the board or, when electrically operated, it may be placed at any distance in the station. The figure also shows the contact elements as consisting of double sets of clips between which wedge-shaped copper blades engage. This gives a double break in each line. The large sizes are more conveniently operated by electric control. Small motors or solenoids may be installed upon them, which are controlled from the switchboard. These motors or solenoids take the place of hand control only and all emergency devices are retained for the operation of the circuit breaker. Various sizes and types are shown in Figs. 145 to 148.

Figure 145 shows a rather small hand operated oil switch of

the Westinghouse make. It consists of knife blades entering the regular switch clip, all being in a tank of oil. This type should not be used to open very heavy currents as the clips and blades are not provided with non-arcing tips.

The second one of the breakers illustrated, Fig. 146, is a switch used by the Lowell Electric Light Company, Lowell, Mass. The oil tank is removed. It is of General Electric manufacture, and

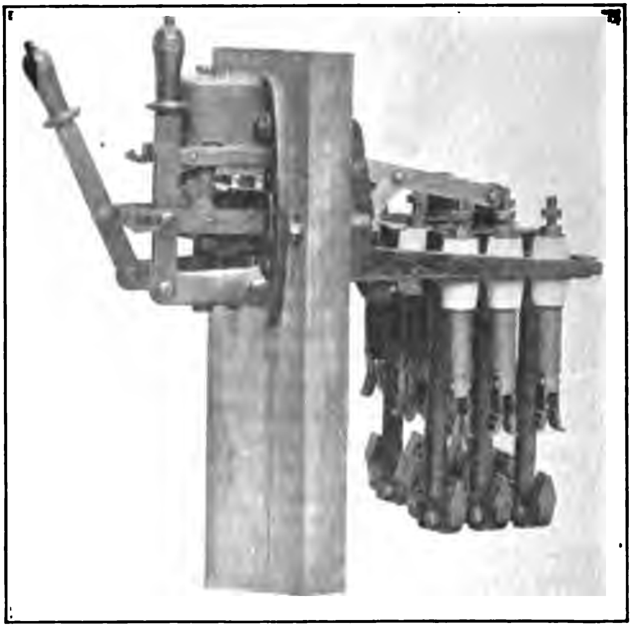


FIG. 146.—Form K-3 oil switch. 150 amperes, 2500 volts.

is called a Type F, Form K-3 oil switch. It is rated at 150 amperes and 2500 volts. It will be seen by the cut that the manually operated handle controls, through toggle mechanism, the wedge-shaped tongue or projection which enters the open jaws above them. An automatic electric release is provided, being placed just between the two handles. As shown, this release has operated and tripped the switch out of contact, although the handle is still at the "in" position.

In Fig. 147 is a large 60,000-volt type G breaker in the shops

of the Westinghouse Electric and Manufacturing Company. Separate tanks are provided for the three phases. Long, well insulated leads come out through porcelain bushings in the tops of the tanks. The operating mechanism is seen below the center tank, being a lever worked by solenoid.

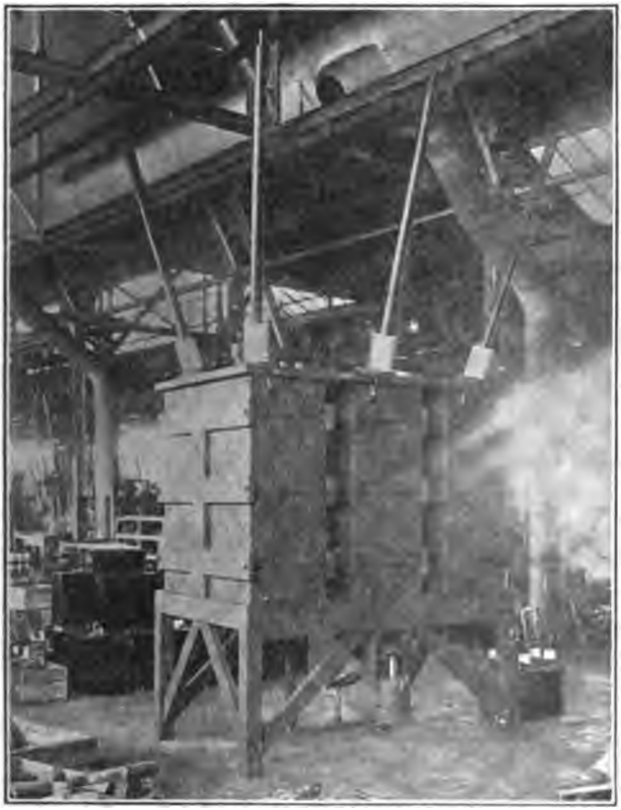


FIG. 147.—60,000-volt, type G. oil switch, electrically operated.

One of the latest developments is shown in Fig. 148, being the oil switch built by the General Electric Company for the Great Western Power Company. It comprises three poles separately assembled in independent tanks. Housings are provided for the mechanism upon each individual member and the whole

switch may be operated by a single hand lever mounted upon suitable framework. The bushings through which the leads enter the oil tanks are of the oil-filled type. This switch is a Form K-10, used upon a 110,000-volt circuit and is rated for 100 amperes.

No oil switch or circuit breaker should ever be installed without a complete realization of what service it may be called upon to per-

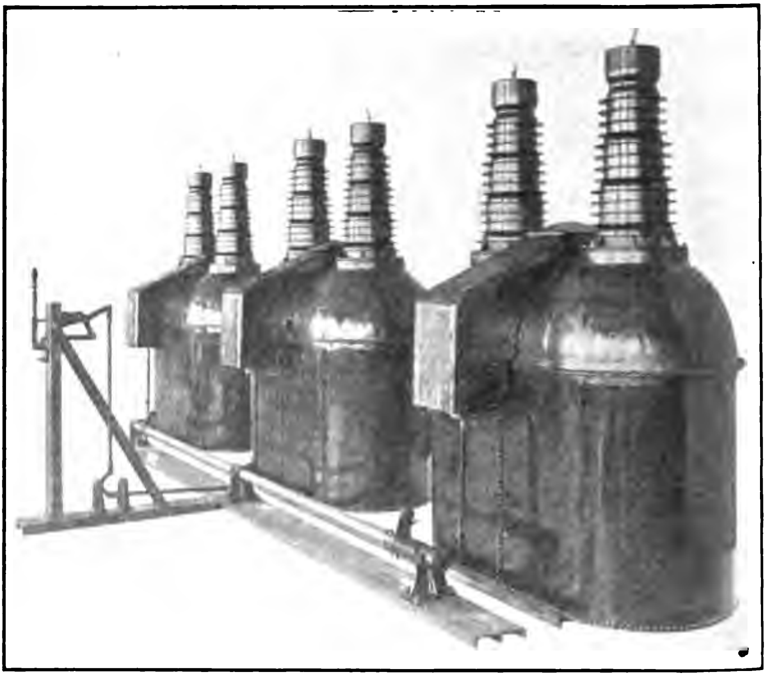


FIG. 148.—Form K-10 oil switch. 100 amperes, 110,000 volts. Great Western Power Company.

form. That is, a certain switch which may properly be installed upon a 100-ampere feeder of a 250-kilowatt system may not be utilized upon a 100-ampere feeder of a 5000-kilowatt system. The point to be remembered is that protective devices are expected to remain idle upon normal conditions of operation, but when abnormal conditions occur, they must act to protect line and apparatus including, if possible, themselves. The magnitude of the

destructive phenomena depends, not upon the number of amperes a line ordinarily carries, but upon the capacity of the plant back of the line, the methods of switching, point of installation of switch, etc. For example, the breaker upon a 100-ampere feeder running from bus bars supplied by five generators will some day be called upon to open the line when the feeder is grounded and all five generators are short-circuited through it. This would be quite a different matter from only one generator. The current rating of such a switch is, therefore, the value of current at which it is intended to operate normally without overheating or opening the circuit. A rise of some predetermined percentage in this current will operate the protective devices. But the kilowatt rating of the switch is that value of power which may be interrupted by the switch without damage to it. Operation upon much greater loads will cause more or less serious injury to the switch and may mean its utter destruction. This kilowatt rating depends somewhat upon the voltage of the system, being lower for higher voltages.

The relays, already mentioned, may be described as auxiliary devices which will open the switches at predetermined conditions of circuit. By their use an energetic, prompt action is obtained, while delicate adjustments of limits are also possible.

The overload relay, operating to protect the circuit in case of heavy currents, may be set for instantaneous action at a certain current value or it may be so arranged that a definite time must elapse before the breaker will open. The desired current limit may then be exceeded for shorter periods, but when the current has been at excessive values for this set time, the circuit will be opened. Again, the inverse time relay will act to open the circuit it is protecting at a certain overload and with a given time element. If the current is greater than this permissible value, the time element required for action is inversely proportional to the excessive current. A short circuit is thus opened instantaneously. This type is a protection against over-heating of apparatus, as with greater overloads the heating is greater and the protecting device shortens the time the machine may carry the excess load. The action of this relay is secured by a bellows attachment or by the damping effect of a magnetic field.

Reverse current relays may likewise have any time action

desired. It is preferable in the case of low voltage relays to have them act without time delay. They are generally so arranged. Reverse-phase relays to protect against improper connections are generally of the instantaneous type also.

For high voltages, these relays are arranged for operation by current transformers or potential transformers upon the main line. The current thus derived serves in one type of relay to close, by solenoid, a local circuit from low voltage direct-current bus bars through the tripping device of the oil switch or breaker.

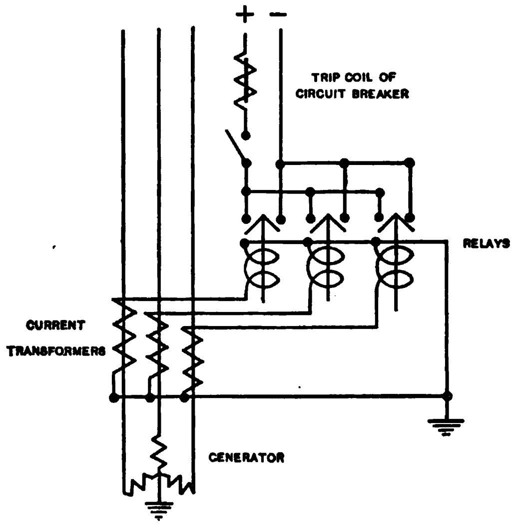


FIG. 149.—Circuit-closing relays, operating direct-current trip coils.

The trip coil is worked by direct current. Where the low voltage buses are not available, types are installed which, by excess current in the solenoid coils, will open a short circuiting contact normally closed across the tripping coil circuit and thus allow the current of the transformer to operate the trip. These details will be understood by referring to Figs. 149 and 150, the former being of the circuit-closing type with direct-current trip coil, the latter of the circuit-opening type with alternating-current trip coil.

Remote electrical control of an oil switch is accomplished by means of a special single-pole double-throw switch. Closing the

switch upward will operate through motor and springs or through solenoid to close the breaker. After contact is made, the operation is automatic and cannot be stopped till it is completed. A signal pointer or light will then indicate that the main circuit is closed. A red light is used for this purpose, indicating a live circuit. It is placed in a conspicuous position just above the control switch. Throwing the control switch in the opposite direction similarly opens the main line at the breaker and leaves control circuit conditions such that everything is ready for the later operation of closing.

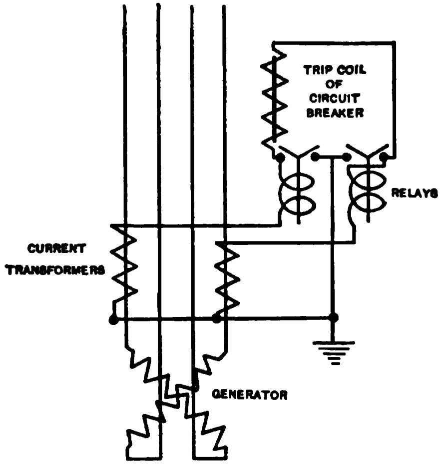


FIG. 150.—Circuit-opening relays, operating alternating-current trip coils.

When the breaker is open, a green light shows on the switchboard just below the control switch. Figure 151 will give a good idea of these circuits and their operation.

Fuses.—Where mechanical control of a circuit by opening a switch is not necessary, where the simple discontinuity of the circuit will introduce a sufficient element of protection, the least expensive form of automatic circuit opening device is, of course, the fuse. It is no more than a wire conductor of designedly low conductivity compared to the remainder of the circuit. It is so installed that it may be easily replaced. The wires used for low current circuits are alloys of varying proportions of metals including lead, tin, bismuth, etc. These are alloys with low

melting points, and hence the wire or ribbon used is mechanically large enough to be easily handled.

However, the rating of fuse wires is much more accurately accomplished with the use of pure metals, especially those having higher melting points. When currents are of magnitude great enough to permit the use of copper or aluminium fuses, they are

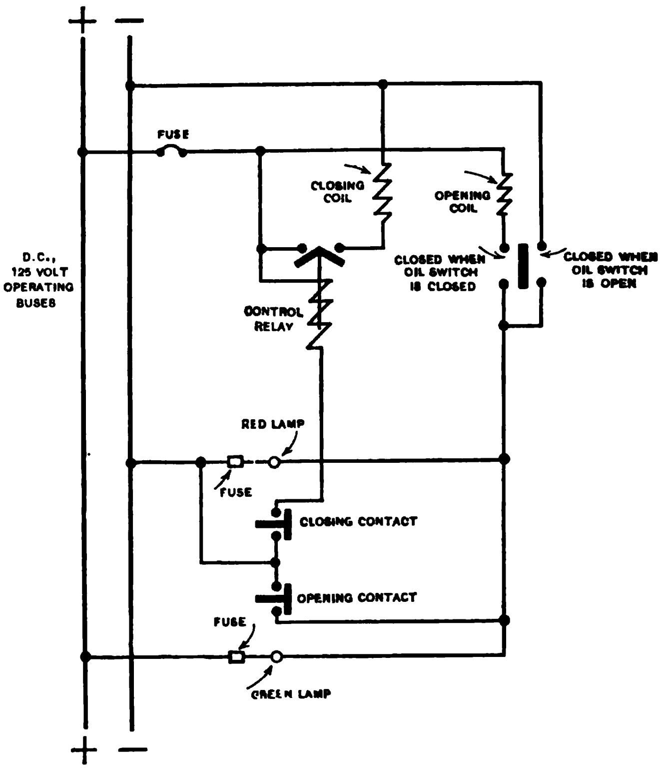


FIG. 151.—Circuits for remote electrical control.

preferable to the alloys and will give less conducting vapor when blown. But the use of copper for such low currents as 10 or 20 amperes would mean a very small wire or ribbon with corresponding inconvenience in handling. Moreover, copper and aluminium are more permanent and constant in current carrying capacity than are the weaker alloys. The latter age to such an extent that their capacities will lower by large percentages in

time. Wherever they are installed they should be inspected frequently and replaced by new. This deterioration is caused by slow corrosion of the metal, due less to oxidation than to injurious gases in the atmosphere. This may progress continuously in small fuses till the whole body of the fuse is rendered valueless as a conductor. Erratic behavior may result, due to the strength of an exterior shell in containing a partially fused interior.

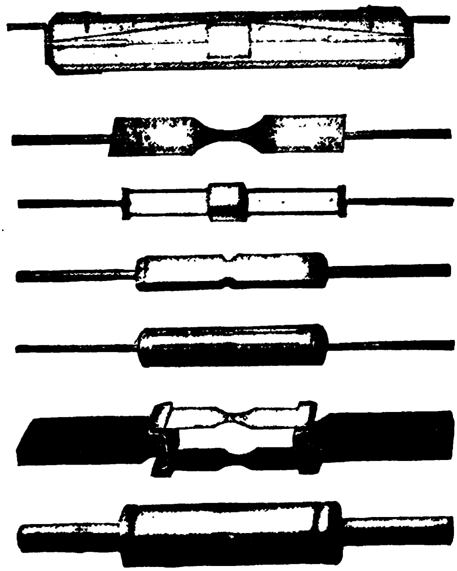


FIG. 152.—Elements of D. and W. fuses.

As the blowing of a fuse depends upon the total heating or what may be termed the integrated value of the heat developed, they should be rated in terms of current and can be made for any voltage.

The actual result depends upon numerous incidental features. The amount of radiating surface may be changed by changing the shape of cross-section. A ribbon fuse will carry more current than will a round wire fuse of the same cross-section. A fuse 1 inch long placed between large copper terminals will cool by conduction much more rapidly than it will if it is installed in lengths of several inches. An enclosed fuse, surrounded by a

packing of non-inflammable material will vary in capacity in a direction inverse to that of the change of temperature. Air enclosed fuses are less affected by temperature changes. Open fuses are very erratic in behavior, if they are placed where they are subject to varying conditions of temperature, air circulation, etc.

The enclosed fuse is frequently provided with an indicator consisting of a fine shunt fuse running to the surface of the container. When the main fuse blows the secondary will likewise fail, leaving a small blackened spot or "bull's eye" to indicate a blown fuse. The elements in construction of fuses for use with

FIG. 153.—Expulsion type of fuse.

currents up to 600 amperes are shown in the group of types of Fig. 152. The small drum-shaped centers of two of the illustrations are simply air-filled cylinders around the fuse. Another one illustrates the secondary or indicating strand, which comes to the surface of the enclosing cylinder at the center.

A type of fuse called the *expulsion type* is shown in Fig. 153. The chamber at its base acts as a recess in which the gases collect when the fuse blows, the expansive force of these gases serving to expel from the tube the vapors over which the arc is maintained.

In the installation of fuses for very high voltages the lengths must be increased to such values that arcs cannot be maintained across the space after the blowout of the fuse. When they are installed outside the power-house, long copper wires may be

used quite advantageously. Another type, built by the Westinghouse Company, is so constructed that upon the rupture of the fuse a spring operates to increase the distance between terminals, thus causing the arc to go out.

Flexibility of Interconnections.—The system so far outlined may give parallel operation of all generators and all lines or

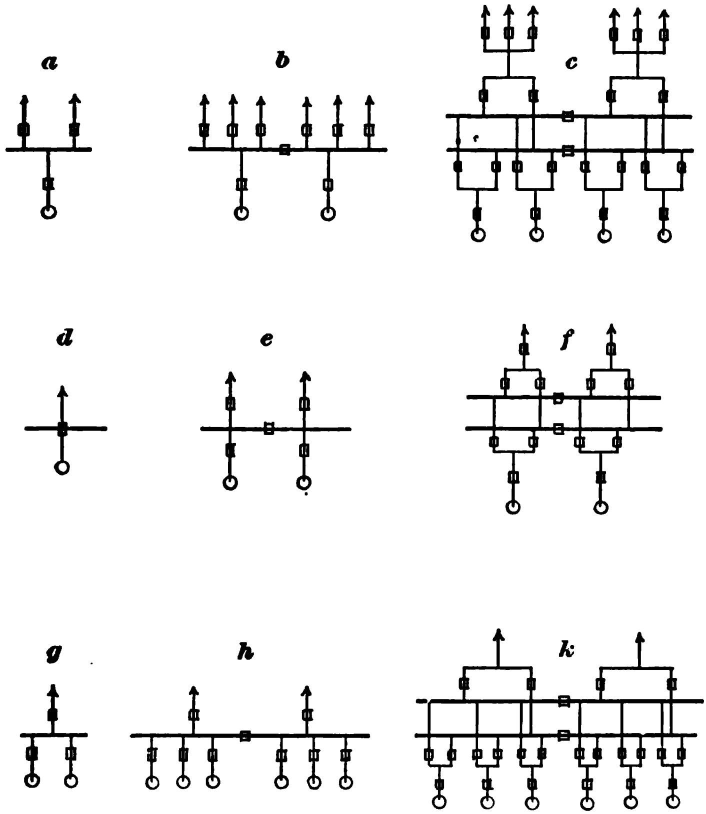


FIG. 154.—Fundamental switching systems.

feeders, or it may be carried only to the extent of grouping a few units together. Generally, all are tied together, but by means of switches so placed that they may be divided into sections at any time desired. It is sometimes desirable to shift the circuits, to interchange generators, lines, or sets of bus bars. In order to

do this, extra bus bars may be provided as well as extra switches, etc. Perhaps a clearer idea of the possibilities of this scheme as well as a better understanding of the necessities, may be acquired by reference to Fig. 154. Generators are indicated by circles, switches of all kinds by rectangles, bus bars by heavy lines, outgoing lines by arrowed lines. Single lines are used to represent complete transmission circuits consisting of two conductors, bus bars, etc., with direct current, or of three conductors, etc., with alternating current.

In the upper row the number of lines exceeds the number of generators. In the middle row the two numbers are equal, while in the lower row the generators are small and more numerous.

In *d* we have the simple unit type. Its enlargement to *e* and *f* leave it still unit type, as already mentioned. One switch only per conductor is necessary in *d*. When paralleled with another, as in *e*, switches increase in number to five if much elasticity is to be attained. Here either generator may be cut off or either line may be similarly severed from the group, leaving them dead for inspection or repair. A *section switch* in the bus bar (dividing it into *sections*) will separate the system into two single, independent systems. Perfect elasticity of connections demands the arrangement shown in *f*, where are shown, in this order, *generators, generator switches, selector switches, bus bars, selector switches, line switches, lines.*

By this arrangement, using double bus bars as well as double selector switches, etc., either generator may be run upon either set of bus bars while the lines may be accommodated with the same degree of flexibility. The system may even be divided into two independent parts with the left hand generator carrying the right hand line and the right hand generator carrying the left hand line. With three or more such units, much flexibility may still be maintained by closing the bus bars upon themselves in rings and providing them with section switches at each interval between generators.

Where units are not possible owing to a large number of lines, or to several generators, groups are arranged. In these groups (*a*, *b*, *g*, *h*,) each generator and each line has its individual switch. With a further development of this, as in *c*, lines may be grouped

and connected through a common switch to either bus bar. This is a *selector switch* because it gives choice between bus bars. It is also a *group switch* because it handles the group of feeders. In *c*, the five switches may be identified as *generator switch*, *selector switch*, *group switch*, *line switch*, and *section switch*.

Illustration *k* is simply an inversion of *c* in point of relative numbers of lines and generators.

The switches shown are not all automatic and with those which are self tripping, time elements may differ.

Generators may be installed without automatic protection at the generator switch, which will then be hand operated. This is allowable because nearly all generators are capable of standing their short circuited current for an appreciable time without injury. The line which is causing the trouble may be automatically cut off before any damage is done to the generator, leaving the latter to maintain service to the other lines. Whereas, if the generator switch should open the entire load might be lost. If desired, however, a timed release may be installed at this point, and this will frequently be seen.

In *c*, *f*, and *k*, the generator switches may be omitted if desired, dependence being put upon the selector switches. Where automatic switches are retained, however, it is often cheaper to use one as generator switch, allowing for non-automatic selector switches. Selector switches which do not need to open under load may be of ordinary air break type. If no generator switch is used and generators are to be disconnected from the line under load, oil switches are needed for this service. There is no greater need of their being automatic than there is for the generator switch. Group switches may be called upon for most severe service. They are automatic and have large capacity. The line switches come into the same category and should be of rugged construction and sufficient capacity, operating with automatic devices. The inverse time relay may be used advantageously in these switches because the more severe the disturbance the more quickly the disturbing line should be disconnected. A short circuit of all generators in parallel through some one group switch or line switch will put most severe strains upon these devices. By installing section switches of the instantaneous type, the bus bars may be sectioned in time to disconnect the

group switch from the major part of the supply and thus very materially reduce the current it must open.

In *f* and *k*, the line switches may be omitted subject to the same arguments as obtain in the case of generator switches in *c*, *f*, and *k*.

Where storage batteries are used, they must be protected by over voltage relays.

It will be noted that the systems discussed are generator-bus bar-line systems, with no intermediate transformation. While they are the simpler case, the presence of step up transformers gives the frequent and important condition pertaining to transmission to longer distances than may be served by the lower voltage method. This service may make use of the two sets of bus bars, low tension and high tension, between which the transformers are paralleled.

The unit type in this case may be any one of three possibilities. Generator and transformer may correspond to each other; transformer and line may form the unit; or generator, transformer and line may constitute the unit. Whatever the unit may be, switching arrangements should be made so that it may be run independently of the other units by wholly disconnecting it from the bus bar or bus bars. With generator-transformer unit, this means the low tension bus bar. With transformer-line unit, it is the high tension bus bar, and with generator-transformer-line unit, it includes both bus bars.

For example, in order to arrange for generator-transformer unit, two switches will be interposed between the generator and the transformer. From the point between these two switches a lead runs through a third oil switch to the low tension bus bar. By opening the first of these three switches the generator is cut off and the low tension bus bar supplies the transformer. By opening the second switch only, the generator feeds to the low tension bus bars, and the low voltage coils of the transformer are disconnected. The high voltage coils may be disconnected from the high tension bus bars and the transformer will be dead. Again, opening the third switch will leave the low tension bus bar out of the unit. The generator then receives or gives no aid except by way of the high tension buses.

In these arrangements, it should always be possible to isolate

any piece of apparatus or line, leaving it dead, in order that it may be inspected and repaired when necessary. This, of course, also serves to eliminate an injured member from the system so that all other parts may work normally.

To summarize relay switching conditions we may designate the following general arrangements as good practice, although great variations therefrom occur with changes in local conditions.

A. C. Generator Circuits.—No automatic protection or reverse power relay with time limit.

A. C. Feeder Circuits.—Inverse time limit relay. Reverse power relay.

A. C. Motor Circuits.—Overload and reverse power relays both with inverse time limit devices, reverse phase instantaneous relay, low voltage release.

Transformer Circuits.—Overload and reverse power relays with inverse time limit coils.

Rotary Convertor A. C. Circuits.—Overload inverse time limit relay.

Rotary Convertor D. C. Circuits.—Reverse current time limit relay.

D. C. Generator Circuits.—Reverse current inverse time limit relay.

D. C. Feeder Circuits.—Reverse current time limit relay, overload inverse time limit relay.

D. C. Motor Circuits.—Reverse current inverse time relay, low voltage instantaneous relay.

Storage Battery Circuits.—Over voltage instantaneous relay.

Switchboard Designs.—It will be seen from the preceding discussions that the number of switches becomes large with increase in flexibility of switching arrangements. When duplicate bus bars are installed this is even more serious. Inasmuch as oil switches are expensive, their profuse use is out of the question, and every effort is made to restrict their numbers to the least possible figures. The wiring is such that high tension lines are not brought to the switchboard, but are controlled therefrom by the auxiliary or relay circuits.

Typical station wiring diagrams are shown in Figs. 155 and

156 where line drawings indicate switchboard apparatus, devices, and mains.

The switchboard itself must be designed with due consideration to the following points:

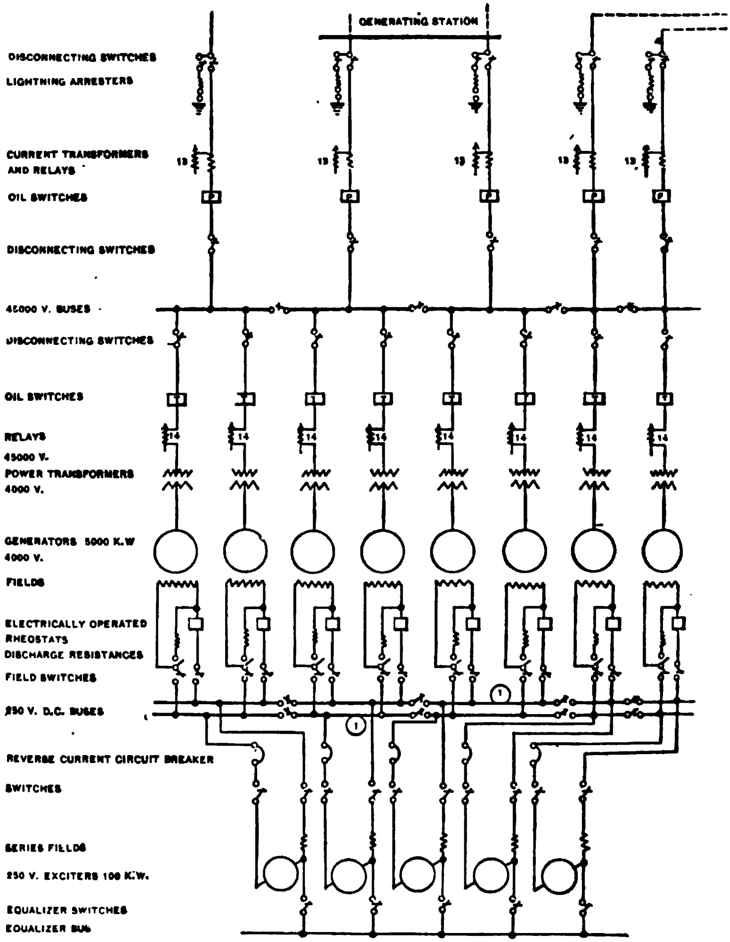


FIG. 155.—Switching systems.

1. Liberal provision for operation as regards capacity, line protection, and flexibility of circuit connections and insulation of members.

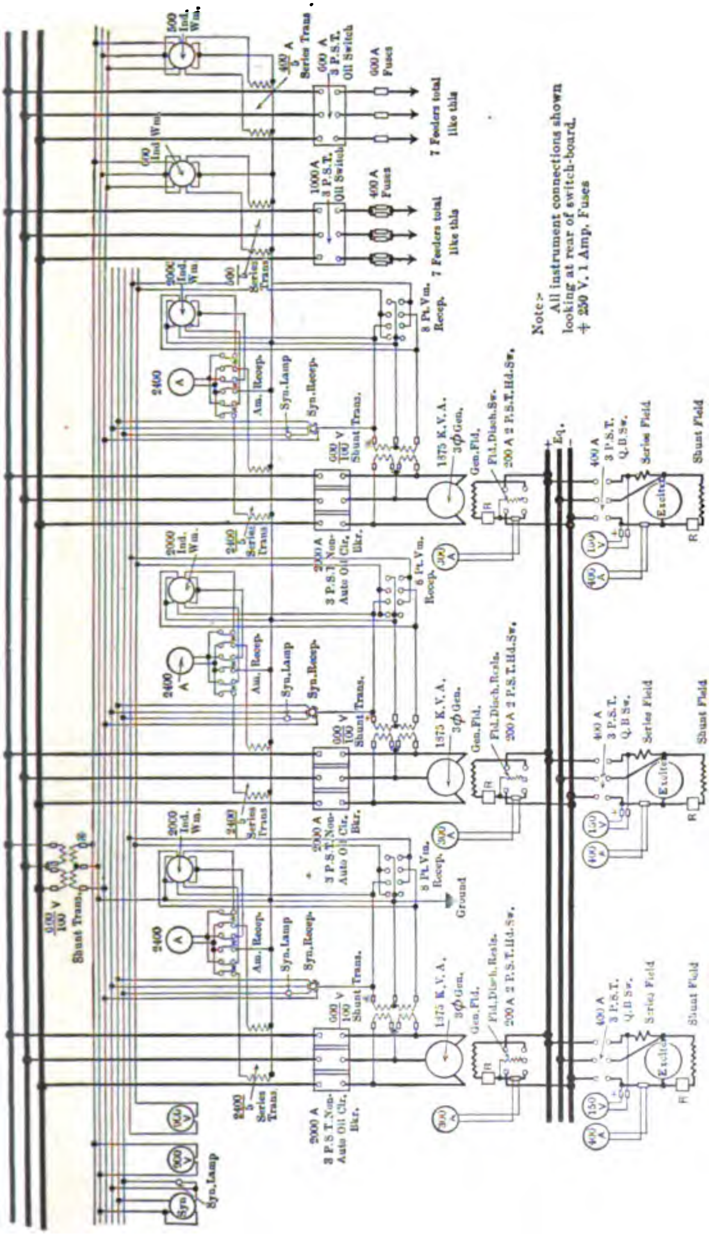


FIG. 156.—Station wiring.

2. High insulation of all line parts.
3. Protection against trouble contagion.
4. Fireproofing.
5. Accessibility of parts.
6. Safety by bringing low potential only to boards.
7. Indicating instruments.
8. Possibility of extension.
9. Symmetry.
10. Fool proof connections.

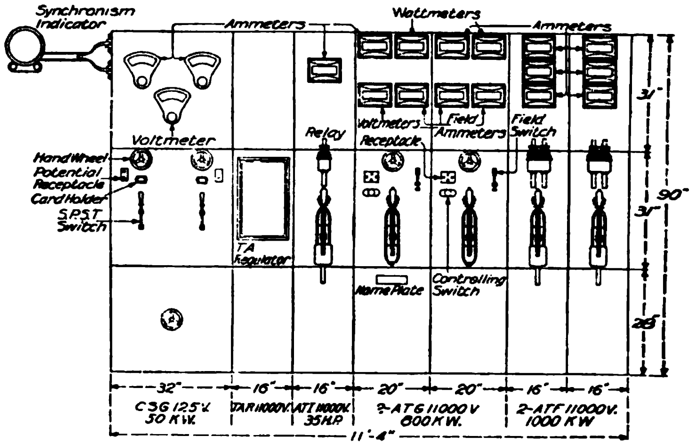


FIG. 157.—Front view, 11,000-volt switchboard.

A suggested arrangement taken from a General Electric bulletin is shown in Figs. 157 and 158. The design is for a small 11,000-volt switchboard for two, three-phase engine driven generators, one engine driven exciter, one induction motor driven exciter and two high tension feeders. It consists of seven panels, arranged for exciter (1), regulator (1), induction motor (1), generators (2), and lines (2).

The exciter panel is shown as accommodating the two exciters. It carries two ammeters, one voltmeter, two rheostat wheels, two potential receptacles or terminals, two single-pole single-throw switches, one equalizing rheostat.

The regulator panel bears one voltage regulator and one potential transformer.

The induction motor panel holds one ammeter, one set of three single-pole automatic oil switches operated as a triple-pole switch with bell alarm switch, one time limit overload relay, two current transformers.

Each generator panel has one ammeter, one polyphase indicating wattmeter, one voltmeter, one field ammeter, one field switch, one synchronizing receptacle, one hand wheel for rheo-

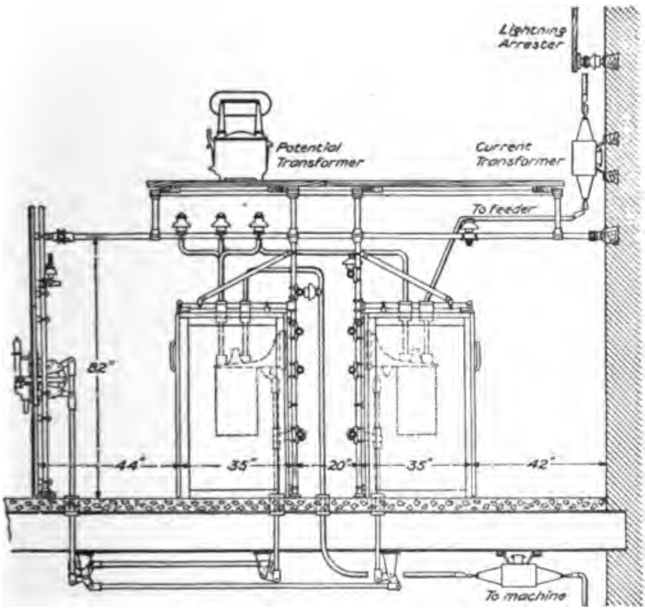


FIG. 158.—End view, 11,000-volt switchboard.

stat, one engine control switch, one set of three single-pole, non-automatic oil switches operated as a triple-pole switch, two current transformers (three current transformers in case of grounded neutral) two potential transformers.

The line panels are each equipped with three ammeters, one set of three single-pole automatic switches, operated as triple-pole switch with bell alarm switch, one time limit overload relay, two current transformers. Wattmeters may or may not be required, as is also the case with watthour meters.

A synchronism indicator is swung upon a bracket arm at the

end of the board. Lightning arresters are installed upon the outgoing lines. A ground detector might be added.

It will be seen that the lines coming from the machines go through current transformers below the floor, thence to the oil switches and the three bus bars (indicated in cross-section upon petticoat insulators). Another oil switch is inserted in reaching each line or feeder. The oil switches indicated are remote mechanical control.

When bus bar potential is high there should be provided individual compartments for each bus, openings occurring in front of each connection. These bus bar compartments may be conveniently located in the basement, the oil switch connections therewith being operated by electrical remote control.

With a synchronous motor the panel should contain one line ammeter, one field ammeter, one field rheostat, one double-pole field switch, one synchronizing plug receptacle, one automatic overload oil switch, one time limit relay, necessary current and potential transformers. To these may be added a power factor indicator and a wattmeter. If the motor is self-starting it is sometimes provided with a double-throw line switch. The starting position connects with low voltage transformer taps or compensator. The running position is served with the regular protective devices.

Rotary converters require two panels, one for the alternating current side and one for the direct current side. The alternating current panel needs, if the machine is to be started from the direct current side, one ammeter, one automatic oil switch with bell alarm, time limit relay, current and potential transformers. There may be added a power factor indicator and when needed, a potential regulator. With the regulator there will be required a double-pole double-throw control switch and a voltmeter. If the rotary converter is to be started from the alternating current side arrangements will be made similar to those for the synchronous motor, a double-throw line switch, etc. The synchronizing device and the synchronism indicator will not be required.

The direct current panel for the rotary converter on two-wire system requires one ammeter, one voltmeter, one circuit breaker, one hand-wheel for rheostat, one three-pole switch for positive

main, negative main, and equalizer, one field switch, one four-point starting switch.

When the converter is started from the alternating current side, the above starting switch is omitted.

Upon three-wire systems, there should be installed two circuit breakers with interlock shunt trip coil and bell alarm and two ammeters, the remainder of the apparatus being about as above.

Rotaries must be so protected, when feeding to direct current bus bars, that the opening of the line switches upon the alternating-current side cannot be accomplished without also opening the direct-current connections. If this is not provided for, the rotary may be running upon a weakened field, when it will race at dangerous speeds.

Direct current generator panels for two-wire system are like those for rotary converters. In either case, the three-pole switch may be replaced by single-pole switches if desired. Low voltage release coils serve to protect the generator in case of falling voltage.

Direct current feeder panel to line may be equipped with one single-pole circuit breaker with bell alarm, one ammeter, two single-pole single-throw switches. The one of these switches upon the same side as the circuit breaker may be omitted if desired.

When a single motor is run from a panel the arrangement should include one circuit breaker, two line switches, one field switch, one hand wheel for field rheostat, one line ammeter, one voltmeter, one field ammeter.

A practice now coming into vogue is the outdoor installation of switching devices and protective apparatus. There is no reason why this cannot be quite successfully developed, despite the difficulties attending. The switches may be electrically operated by remote control methods. Apparatus already used thus includes lightning arresters, high tension bus bars, air break switches, oil break switches, fuses, etc. Even transformers are suggested as suitable for such installation and are being occasionally so placed (see Chapter XI, Fig. 237).

Lightning arresters are installed upon the lines at the points of entrance, the intention being to make this the first piece of apparatus reached by incoming line disturbances, thus providing

protection for all station apparatus. There should be disconnecting switches upon each side of the arresters with one side running to line and the other side leading to ground.

The ground connection must be very carefully made and must be ample. They are already described under Aerial Line Construction. It should be noted, however, that the leads from the arrester to the ground plates or pipes should be short. If the best grounds are necessarily distant from the arrester, as may be the case when connection to water pipes or gas pipes, etc., are used, an auxiliary ground should be made at the closest point possible by driving iron pipes into the earth. These artificial grounds are much increased in effectiveness if they are wet with salt water occasionally. They should be inspected and tested frequently. A sufficient number should be provided to give a combined resistance as low as two or three ohms.

Choke coils or reactance coils are generally installed with arresters. They are placed in the line between the connection to arrester and the station apparatus. They are of low reactance except for the high frequency currents of lightning discharge, and their office is to divert this discharge from the station wiring to the arrester and ground. Several types are in use, air insulation and oil insulation being preferable to solid dielectric because of their self restoration after sparks have passed from turn to turn. Helical coils, "hour-glass" coils, and "pancake" coils are all used. Iron cores are not used because of the high reactance they would introduce at ordinary line frequencies.

Figure 159 shows the method of inserting these reactance coils in the main line as it enters a metallic conduit or pipe leading underground to the substation. In parallel with the line to substation is a line running to one side of a horn arrester, the other side of which is grounded. The metallic pipe ends in an enlarged three-opening *pothead.* This is a metal casing to prevent the concentration of electrostatic stresses at the mouth of the small tube and the consequent liability of breakdown at this point. They are always used when power cables enter or leave metallic sheathing or conduit.

The arresters used are quite varied. They include high resistance, series gaps, single gap horns, electrolytic, etc. They are used separately and in combinations. Direct current circuits

may be protected by high resistance grounds as through carborundum blocks, etc. This prevents cumulative charge. One form taken by the high resistance ground is that which has been used abroad. A jet of water plays against the line conductor,

FIG. 159.—Leading aerial lines underground.

thus grounding it through the high resistance of the water jet. This type may be combined with the horn gap. In fact, the latter one is often used with almost any other type of arrester. It takes its name from its resemblance to a pair of ram's horns. One of the metal horns leads to line, the other to the ground. When a discharge takes place across the short gap at the base of the arrester and dynamic current follows, the heat of the arc causes the points of contact of arc with horn to rise, thus lengthening the arc which eventually goes out because of this increase. The gaps required with different voltages are shown in the curve of Fig. 160.

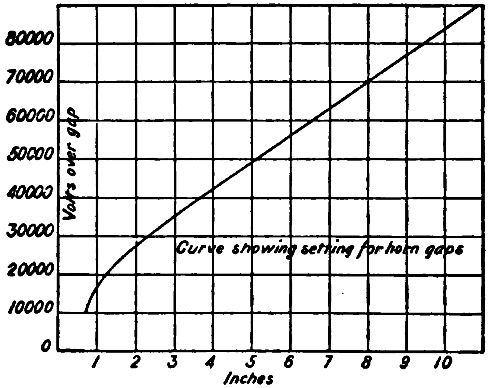


FIG. 160.—Horn-gap setting.

Horn gaps are frequently installed with two or three in series.

The horn type of arrester is seen in Fig. 161. This particular installation is at the Schenectady end of the 30,000-volt Schaghticoke-Schenectady transmission line. The horn gaps lead to the aluminium (electrolytic) arresters inside the brick building. The power lines lead downward from a point just in front of the horn gaps through roof bushings to choke coils and switches to interior wiring. When thus arranged, it is necessary to mount the horns so that the gap may be closed by bringing the two together. This gives the means of "charging" the aluminium arrester, the necessity for which being discussed later. The horns are mounted on line insulators supported by iron piping. By rotating one of the insulators of each pair, the offset horns revolve and come into contact with the stationary members.

The multigap arrester primarily consists of a variable number of gaps in series with each other. They are arranged by placing small metallic knobs at regular distances upon porcelain bases. The individual gaps are about 1/32 inch in length and vary in number according to the voltage of the line. They are grouped in units having 6 to 32 gaps per unit and successive units are installed in series with each other in order to complete the number required.

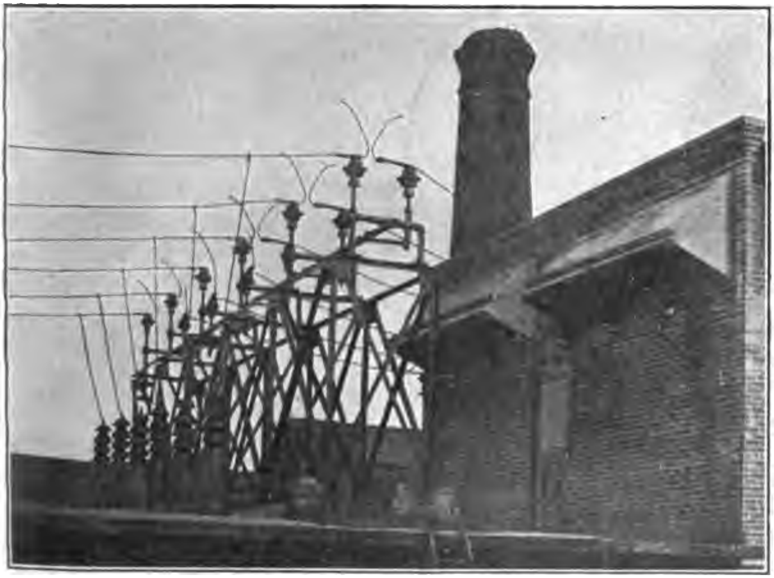


FIG. 161.—Horn gaps installed with aluminium arresters on Schenectady Power Company line.

The knobs are cylindrical in shape with knurled surfaces. They are of special non-arcing alloys of copper with mercury, zinc, etc. These alloys have a rectifying effect upon alternating currents and an alternating arc will go out between such terminals at much higher voltages or with much higher current discharge than it would over other materials. This is the reason of the designation as non-arcing metals. They cannot be used on direct current line protection.

To further increase their effectiveness for the lower voltage

static discharges required of the long series of gaps used upon high voltage work, portions of the series are shunted by resistances of graded valves. The arrangement as used by the General Electric Company places a low resistance in multiple with the first part of the series gaps. A medium resistance parallels this and more gaps, and a high resistance shunts both lower resistances and more gaps.

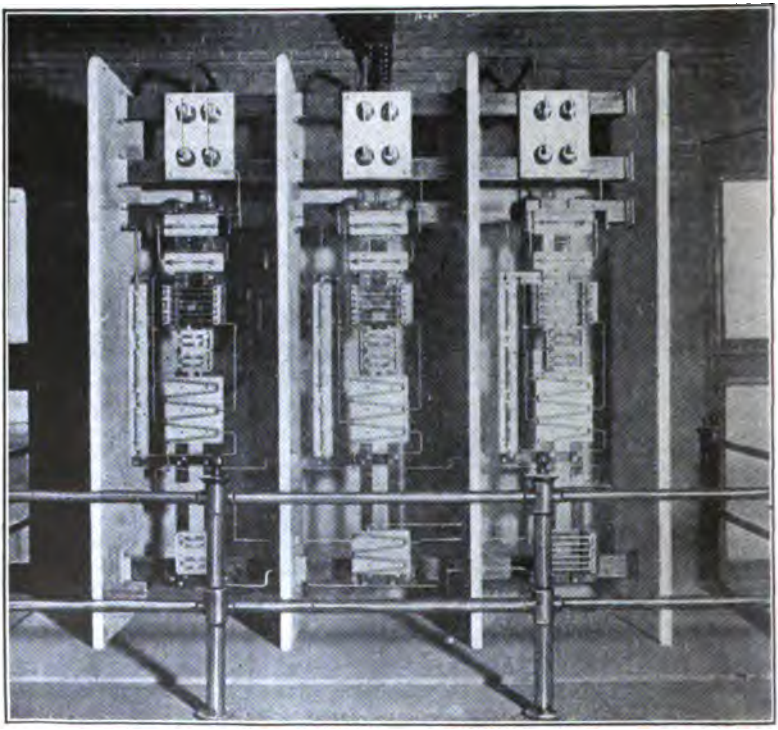


FIG. 162.—Multigap lightning arrester installation.

This gives several parallel paths for the greater part of the length of the arrester gaps. Heavy discharges will not occur over the resistances, but will break down the gaps. Light discharges will not occur over all the gaps but will take one or more of the parallel paths and a reduced number of gaps.

Shunted resistances render the dynamic arc unstable and help

to rupture it. Series resistance will tend to restrict the dynamic current and to put out the arc. At the same time it will also restrict the discharge. Its use is therefore a matter of choice.

Figure 162 shows the installation of a 12,000-volt, three-phase multigap lightning arrester in the Garfield Park substation of the West Chicago Park Commission. After the incoming leads pass to the line switches the line runs to fuse and spark gap in parallel, thence to the shunt resistances and the head of the gap series. The three legs are connected Y and grounded through another gap series shown at the bottom of the center panel. The legs are separated by partitions.

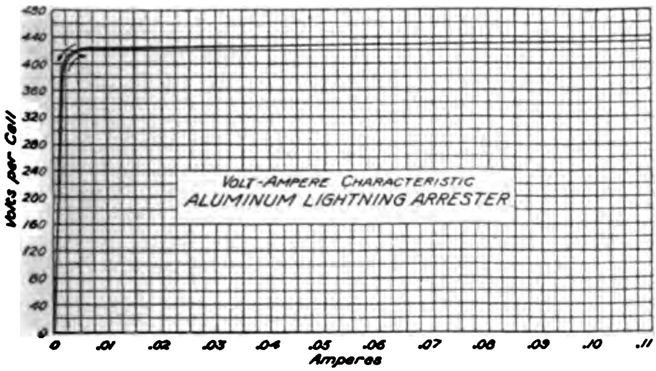


FIG. 163.—Volt-ampere characteristic of the aluminium cell.

When the single gap is used for lightning protection upon direct current circuits it is set in the field of a magnet which will rupture the arc. The multiple gap is not applicable to direct current circuit protection.

The most recent type of lightning arrester developed especially for the higher voltages is the electrolytic arrester.

The volt-ampere characteristic of an aluminium cell shows rapid rise in voltage for nominal increase of current until a certain critical voltage is reached. Beyond this point (about 400 volts direct current and about 325 volts alternating current, depending upon the electrolyte) small increases in voltage are attended by very rapid increases in current. Figure 163 shows this feature and applies only to permanent conditions. When any voltage is applied to the cell a current will flow, which, by electro-chemical

action, forms a film upon the plates. This reduces the current to a low value, a mere leakage current. This is the value meant by the term "permanent." If the voltage is then raised, another current rush takes place until it is cut down by increased film thickness to its new leakage value. The critical voltage once reached, a continued reduction of current does not take place. A lowering of voltage will be attended by a slow dissolution of the excess film. A cell in which the film is formed for a certain voltage is said to be "formed up" for that potential.

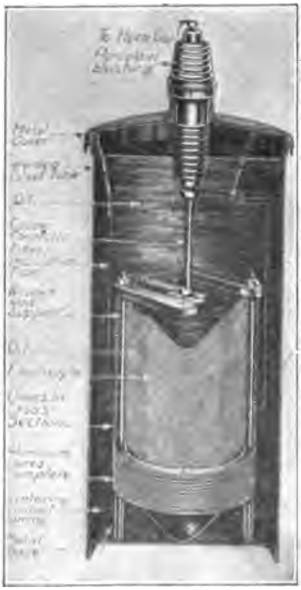


FIG. 164.—Assembly of aluminium lightning arresters.

A cell, which, then, is formed up for 250 volts, if suddenly impressed with a greater voltage will allow a heavy current to flow through it momentarily. The applicability of this unit to the protection of circuits from disturbances due to lightning, etc., is quite evident.

The cells are put in series with each other in large numbers, thus providing for any line voltage met in practice. In order to economize in space the aluminium plates are made in the form of cones or trays and are assembled on side or center rods. The cone is typical of General Electric practice and the tray represents Westinghouse units. These cones or trays are set one within another, being spaced at about 0.3 inches by insulating rings upon the non-conducting rods which hold them in place. The electrolyte is then placed in the series between the cones. The assembly of the General Electric type is well shown in Fig. 164. The prevention of evaporation of electrolyte and the cooling of the apparatus are both provided by immersing the unit in an oil tank. Radiation from the surface of the tank will be ordinarily sufficient. Where this is not enough, cooling coils may be used. For lower potentials, up to 7250 volts, the sepa-

rate stacks of cones for different legs may be placed in the same oil tank. Above that voltage they are given individual tanks.

As before noted, a cell connected permanently to line will have a continual leakage current. With alternating current, this is increased by a capacity current which is, in reality, much the greater of the two. With an arrester permanently connected, these component currents add as vectors and introduce unnecessary loss of energy to the system, and, what perhaps is more important, by these losses keep the electrolyte and oil heated, decreasing their effectiveness when called upon to dissipate the energy absorbed by the unit in a lightning discharge. For this reason gaps are used with each leg.

For low voltage, small horn gaps may be used or gaps between non-arcing metal cylinders may be installed. For the higher voltages horn gaps are invariably used. This practice has been illustrated in Fig. 161.

It will be recalled that when a cell is left disconnected from the line the film loses a part of its effectiveness. The solid portion of the film remains, but a supposedly liquified constituent is dissipated. A cell, therefore, which is left permanently detached from the line, as by the horn gaps, will allow discharges to pass over it; but it is in no condition to open the path to ground for the dynamic current of the line which follows a spark across the horn gap. It will not decrease the current and rupture the arc at the gap until it has regained its proper film. This, although a comparatively rapid process, is exceedingly slow when timed in comparison to incidents of electric circuits. Hence, it becomes necessary to maintain the film upon each plate in a condition suitable for operation at any time. It is found that forming up or charging the cell about once a day is all that is necessary.

In order to do this, the horn gaps are arranged to be closed for an instant by an attendant, being left open normally. Closing these gaps will place the three *Y* connected units across the line and charge them. The unit which is connected between the *Y* point and ground is not impressed with voltage under these conditions. A special interchanging or transfer device is arranged to allow replacing one of the leg units by the grounded unit, voltage again being applied to the *Y* connected units with the new member as one of the three legs.

Use is often made of auxiliary resistance in charging the arresters. The practical method of accomplishing this is by means of an auxiliary horn gap. The normal gap is provided between one regular and one "crumpled" horn. A third horn, placed above the "crumpled" one, approaches the regular horn more closely than the lower pair approach each, other making a second gap shorter than the regular gap. The third horn is then connected through series resistance to the crumpled horn (see Fig. 165). In charging, the smaller or secondary gap is the one closed by the revolution of one horn. The charging current then passes through the resistance in series with the cells.

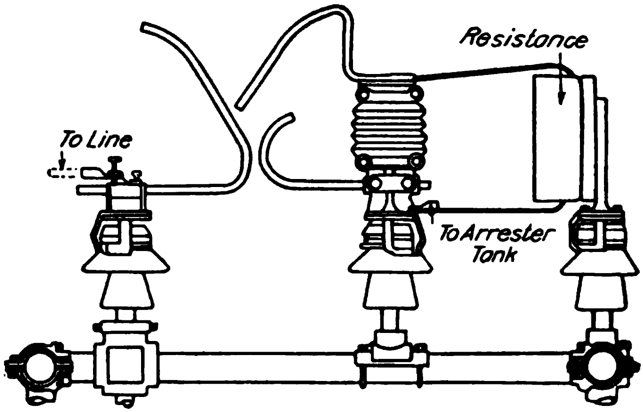


FIG. 165.—Auxiliary horn gap and charging resistance.

The presence of series resistance introduces new characteristics into an oscillating circuit. The oscillations are damped out by the energy losses in the resistance. The "attenuation factor" of the discharge is changed so that the current becomes more rapidly decrescent. Excess resistance still further alters the conditions to the extent of changing the oscillatory attenuation factor to the logarithmic factor. This is the reason for insertion of resistance as above, and by this means the liability to voltage rises and resonance troubles is practically eliminated.

The above arrangement of two parallel gaps also provides the selective paths already spoken of in connection with the multigap arrester, namely, one normal gap for heavy discharge with no

series resistance and one short gap for lighter discharge with the series resistance.

The electrolytic lightning arrester is installed either indoors or outdoors. Freezing the electrolyte leaves the arrester still in working condition but with greatly reduced efficiency due to the increased resistance of the frozen liquid. They should, therefore, be protected from low temperatures (below 20° F.). If

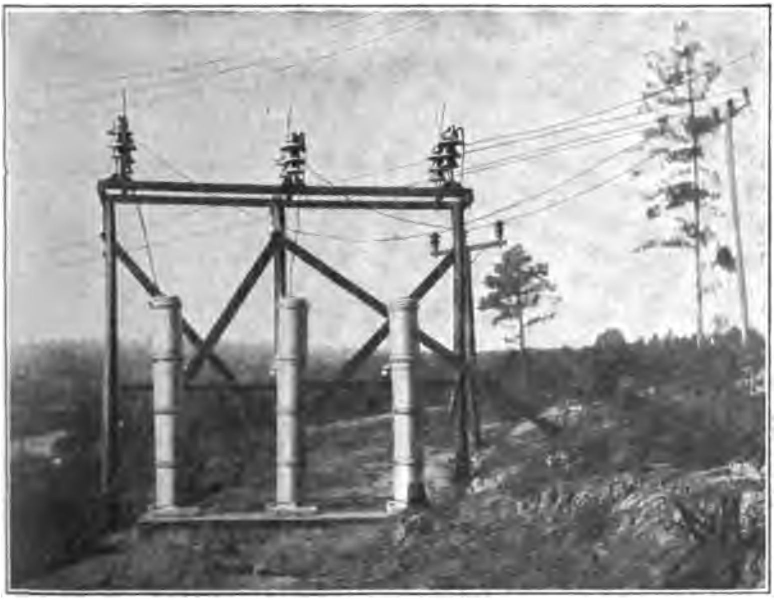


FIG. 166.—Outdoor installation of Westinghouse aluminium lightning arresters.

frozen and then thawed, the electrolyte in its liquid state is not injured and remains perfectly effective.

An outdoor installation of the Westinghouse type of arrester is shown in Fig. 166, and an indoor installation of General Electric manufacture is shown in Fig. 167.

When a three wire system is run with grounded neutral, lightning arresters are connected in Y with the neutral grounded. When the line is run ungrounded, the arresters are connected Y with the neutral run through a fourth unit to ground. It is thus arranged so that there will be two leg units between lines in

all cases except when in the first a line grounds. This, however, causes a dead short circuit, and will open switches. In the ungrounded Y or the Δ, one of the conductors may become grounded and the line may operate this way on emergency. Because of the fourth unit in this case, there will still be two units between any two legs.

A very useful device for installation with lightning arresters is a discharge recorder. A clock-fed paper roll passes between

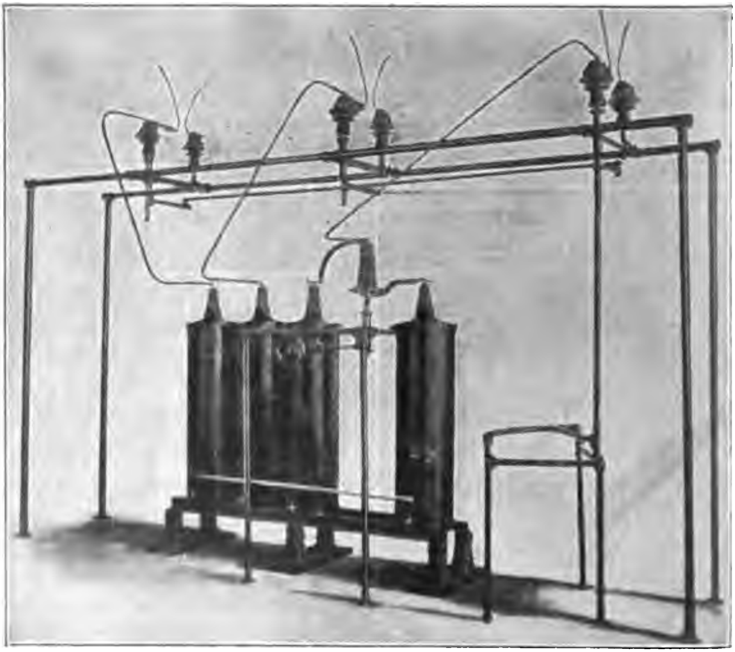


FIG. 167.—Indoor installation of General Electric aluminium lightning arresters.

finger points between which sparks pass when discharge occurs through the arresters. The paper thus provides a definite record of the time when discharges occur and their relative severity. These oscillatory discharges or surges may be due to lightning disturbances or they may be caused by switching, by grounded circuits, by short circuits, by careless operation when machines are thrown in, by combination of certain circuits and lines, etc.,

etc. As each discharge is timed, its definite cause is quite generally recognized, and where the reason for discharge is unknown investigation should be made.

The record also shows to an extent whether the arresters are adapted to the lines upon which they are installed. Frequent discharge with no serious cause will lead to an increase in the number of series cells, while very infrequent discharge may indicate that fewer cells are advisable.

Regulators.—The Tirrill regulator used to maintain constant voltage at a desired point is installed upon a switchboard panel.

FIG. 168.—"Tirrill" voltage regulator.

It operates upon the principle of a floating contact which alternately opens and closes a circuit shunted across the exciter field rheostat. The excitation of the exciter varies thereby and, in turn, this regulates the field current of the generator. The relative time of closed circuit or open circuit across the field rheostat is regulated automatically, and the exciting current is constantly varying between the two extremes corresponding to each permanent condition. It is mounted directly upon a switchboard panel shown in Fig. 168. The elementary diagram shown in Fig. 169 will give a clear idea of its parts and its operation.

The regulator has a direct current control magnet, an alternat-

ing current control magnet, and a relay. The direct current control magnet is connected to the exciter bus bars. This magnet has a fixed stop-core in the bottom and a movable core in the top which is attached to a pivoted lever having at the opposite end a flexible contact pulled downward by four spiral springs. For clearness, however, only one spring is shown in the diagram. Opposite the direct-current control magnet is the alternating-current control magnet which has a potential winding connected by means of a potential transformer to the alternating-current generator or bus bars. There is an adjustible compen-

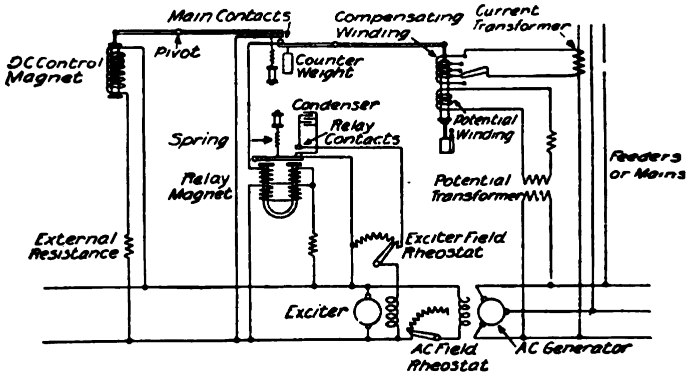


FIG. 169.—Elementary circuits of the Tirrill regulator.

sating winding on the alternating-current magnet connected through a current transformer to the principal lighting feeder. The object of this winding is to raise the voltage of the alternating-current bus bars as the load increases. The alternating-current control magnet has a movable core and a lever and contacts similar to those of the direct-current control magnet, and the two combined produce what is known as the "floating main contacts."

The relay consists of a U-shaped magnet core having a differential winding and a pivoted armature controlling the contacts which open and close the shunt circuit across the exciter field rheostat. One of the differential windings of the relay is permanently connected across the exciter bus bars and tends to keep the contacts open; the other winding is connected to the exciter bus bars through the floating main contacts and when the

latter are closed neutralizes the effect of the first winding and allows the relay contacts to short-circuit the exciter field rheostat. Condensers are connected across the relay contacts to prevent severe arcing and possible injury.

The circuit shunting the exciter field rheostat through the relay contacts is opened by means of a single-pole switch at the bottom of the regulator panel and the rheostat turned in until the alternating-current voltage is reduced 65 per cent. below normal. This weakens both of the control magnets and the floating main contacts are closed. This closes the relay circuit and demagnetizes the relay magnet, releasing the relay armature, and the spring closes the relay contacts. The single pole switch is then closed, and as the exciter field rheostat is short-circuited the exciter voltage will at once rise and bring up the voltage of the alternator. This will strengthen the alternating-current and direct-current control magnets and at the voltage for which the counterweight has been previously adjusted the main contacts will open. The relay magnet will then attract its armature and by opening the shunt circuit at the relay contacts will throw the full resistance into the exciter field circuit tending to lower the exciter and alternator voltage. The main contacts will then be again closed, the exciter field rheostat short-circuited through the relay contacts, and the cycle repeated. This operation is continued at a high rate of vibration due to the sensitiveness of the control magnets and maintains not a constant but a steady exciter voltage.

It can compensate for line drop, thus maintaining constant potential at a distant point. Moreover, types are available which will control two or more generators in parallel.

CHAPTER VII.

CIRCUITS.

In the simple extreme, circuits are classified accordingly as they may consist of one continuous conductor leading successively through all elements of the load, or by conductors with many subdivisions and branchings, portions of the load being

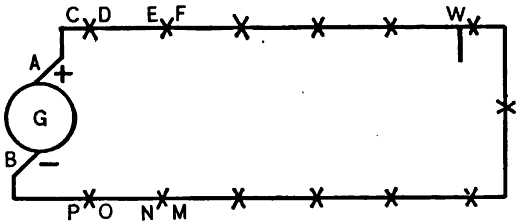


FIG. 170.—Series circuit.

carried upon these elemental parts of the line. The former (Fig. 170) is known as the *series circuit*, while the latter (Fig. 171) is called a *parallel circuit*. The simplicity of the diagrams shown gives place in practice to branchings, combinations, and ramifications until the circuits become very complicated. Each of these

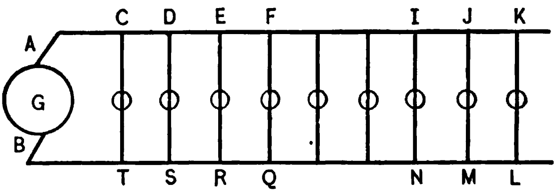


FIG. 171.—Parallel circuit.

systems has its own special applications, but the parallel distribution is most commonly seen.

The series system is applied by unit circuits. The conductor leaves the generator, passes to each lamp, transformer, motor, etc., of the load and after making a loop covering all the territory to be served, it returns to the generator, thus completing the

circuit. As all elements of the load are made sections of the complete circuit, whatever current passes through the generator must pass through each of these load elements. A load unit can be added to or removed from the circuit by opening the conductor at the desired point, inserting or removing the unit, and again closing the circuit. The addition of the unit will not change the value of the current demanded by the circuit. It will, however, introduce a greater resistance or impedance into the circuit and, consequently, in order to maintain this value of current, additional voltage must be generated. With the alteration of load, therefore, the voltage generated will vary, the current supplied will remain the same as before. This series system may be spoken of as a *constant current system.*

The parallel system is secured by multiple divisions of the circuit. Leaving the generator, the conductor branches, each branch supplying an element of the load, and all branches being again united in a single conductor passing to the second generator terminal. To decrease the load the switch in any elemental branch circuit may be opened *and allowed to remain open.* This decreases the current demanded by the load as a whole. In fact, it increases the resistance of the load by making fewer the parallel paths, each of a definite resistance. In order that each element shall receive the same current as before, the voltage across its terminals must remain constant. Here, then, current varies but voltage remains constant. Hence, we have what is generally spoken of as the *constant potential system.*

The loss in each case may be considered, in the most general way, as being measured by the heating of the conductors. Due to the resistance of the conductors, there is required a certain voltage to maintain the flow of energy toward the receiving unit.

Suppose the load units of a series system are concentrated at points uniformly spaced as in Fig. 170. If we measure the voltage between the points A and B we will read the full voltage of the generator. Between B and C the reading is less than before by the voltage necessary to give the energy flow through the section AC. From B to D the voltage is less than from B to C, by the amount required for the element of the load. These differences are called the *drops in potential* along the line or across the load. Plotting the *readings* (not the drops) we have such a curve as is

shown in Fig. 172. This curve may be called the *potential gradient* of the line and may be referred to any point as zero value instead of the point B above chosen. The curve would then be shifted to such a position that the zero line would cross it upon the point corresponding to the chosen point of the line. This becomes important in the consideration of grounded lines and the potential to ground of any other portion of the line.

When once the potential gradient is plotted, having taken any point as reference point, we may use it as follows:

Pass through the point upon the curve corresponding to the

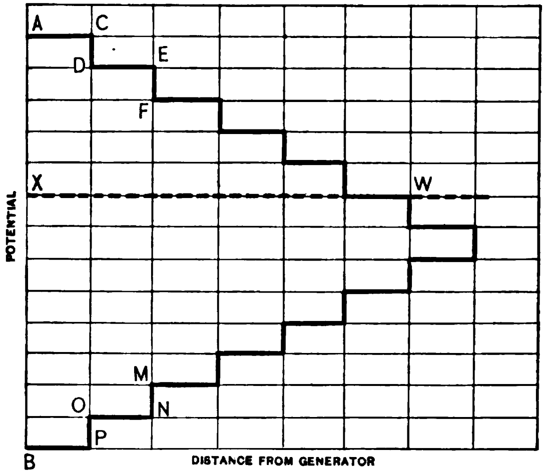


FIG. 172.—Potential gradient for series circuit.

grounded point of the circuit a horizontal line. This line is zero potential. The voltage between any point upon the circuit and ground will then be read from the curve referred by the original scale to the new zero line.

For example, in the circuit shown in Fig. 170 a ground occurs at W upon the positive side of the sixth lamp from the positive brush (A) of the dynamo. This point of the circuit is, then, at zero potential. The line XW (Fig. 172) now becomes the axis of the coordinates for the gradient curve and the greatest voltage to ground occurs at the point B, the negative brush. That point differs from ground potential by the amount BX, the voltage over eight lamps and the intervening conductor. Ground-

ing the midpoint of the line (or the dynamo if possible) will give smaller maxima between line and ground than grounding any other point. Similarly, connecting either brush to ground will give the largest possible reading.

The energy expended in the elements of the system is measured by the product of the voltage drop across the part considered into the current of that part. (We will assume for the time being that the power factor is unity.) Hence, the energy expenditure in any one section of the conductor will be measured by the product of the current (a constant) into the voltage reading between the two ends of the section. This latter depends in value upon the resistance of the conductor by the law

$$e = ir$$

and is indicated upon the potential gradient by the change in level of the curve. A steep curve will indicate a considerable absorption of energy. Hence, the potential gradient will be steep at the load units and gently sloping between them.

The energy absorbed by the conductor sections is dissipated as heat and is a distinct loss. That taken by the load is expended more or less completely in the method for which the unit is designed. High efficiency of the system demands small losses in the line and concentration of energy expenditures in the load units, where also intrinsic losses must be kept as low as possible.

The line resistance may be reduced with increased expense for material for the conductor and its support. The balancing of increased expenditures (computed upon the annual basis) against the value of the power saved thereby constitutes one fundamental idea in the design of series circuits. Add to this safety and quality of service and the items are nearly all present for the determination of the proper specifications.

The series circuit is very important in lighting systems. It is used both with incandescent lamps and with arc lamps. It rarely occurs elsewhere, except in the case of single unit generator and load. This simple extreme is, of course, the embryo of either system.

In arc lighting the current values standard now are quite numerous, varying from 2 amperes to 12 amperes.

Underwriters' rules demand for safety that conductors used shall be no smaller than No. 14 B. & S. gage.

Lamps are liable to fail by burning out, breaking the carbons, etc., in which case they must be eliminated from the circuit. This is accomplished by the use of *cutouts*. A solenoid coil shunts the lamp. When the arc is extinguished, the solenoid closes contacts, shunting the lamp.

Here (1) the cutout circuit must contain enough resistance to shunt some current through the solenoid coil if it is required for maintaining the contact, (2) the contact once made must hold by spring or gravity, or (3) a series coil must come into action in the cutout circuit to hold the solenoid plunger in place. Cutouts may work by gravitation alone. It is important in some cases that the lamp may be actually cut off from the circuit rather than merely shunted by a parallel path. As long as it remains attached to the main circuit it is impossible to handle it in repairing, etc., because its potential against ground may be high enough to kill the repair man. This may be done by use of an auxiliary, hand-operated switch in conjunction with the usual cutout.

When the cutout operates and a lamp is taken from the line, current remaining constant, the voltage supplied to the line must be reduced by the amount across one lamp in operation. This regulation of voltage is accomplished by the regulating device upon the generator. This may also be arranged by the use of a constant current transformer. The different apparatus used for development of these lines will be described later (see Chapters IX and XI). The maximum voltage ordinarily seen upon series arc circuits is about 10,000 volts. This limit is set by successful commutation requirements in direct current work and by safety in both alternating and direct current practice.

In series incandescent systems, the lamp used has a thick short filament of low resistance. The main requirements here are much the same in principle as with the arc lamps.

Cutouts are greatly simplified owing to the low voltage required by each lamp. They consist of two spring clips electrically placed across the lamp. They are separated by a thin paper which punctures when the lamp filament fails.

The power factor of a series arc lighting system is generally in the neighborhood of 0.65 to 0.70, although the arc itself will have a power factor from 0.85 to 0.95.

The potential gradient for a parallel system of distribution may be shown in connection with Fig. 171. Suppose equal units of load uniformly spaced as in the figure. Our curve must, then, show the potential drops through each one of the several multiple paths. In order to do this, we will again plot voltage reading to B against distance from the generator (see Fig. 173). The reading from A to B is plotted at zero distance from generator. Voltage BC is at unit spacing from generator, etc. The vertical distance CT is the voltage reading across the first lamp; DS across the second, etc. The drop in voltage along the line

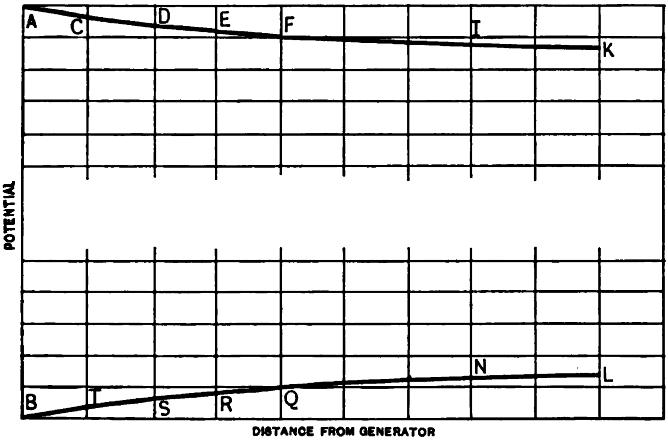


FIG. 173.—Potential gradient for parallel circuit.

from A to C is shown by the falling off in altitude of the upper potential line.

At the point C of Fig. 172 the current divides and only a reduced amount follows the main conductor to D where again a reduction takes place by the amount required for one unit of the load. In Fig. 173 this will be indicated by decreased steepness of the gradient, because, with reduced current and constant resistance (due to uniform spacing of load in this case) the ir product is lessened. Each successive section of the gradient, therefore, becomes less steep. The upper curve of the gradient, AK, has its counterpart in the lower curve BL, where changes in level, or voltage drops, are identical with those above.

It will be seen at once that the voltages supplied to any two

lamps are different. The amount of difference is a measure of the force required to transmit a varying amount of electrical energy along the conductor against the resistance of the circuit. As in the case of the series circuit, the energy expended in this propulsion is measured by the product of the voltage drop across the unit length of conductor into the current in that section. It appears as heat, the energy of irregular molecular motion.

This line loss is kept as low as possible, consistent with cost,

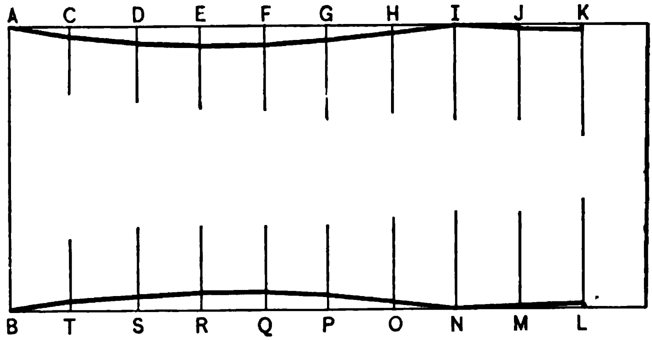


Fig. 174.—Potential gradient with feeders.

etc., by reduced resistance of line. Hence, while the voltage readings across lamps vary according to the location of the lamps in the system, this variation is small compared to total voltage readings and we may call the system a constant potential system.

The construction of this system in order to attain as nearly as possible uniform voltage across similar load units, is not restricted to the enlarging of the main conductor or the *main*. If it is found that lamps out toward the end of the line or motors in that vicinity or street cars at a distance from the power-house are not receiving their power at high enough potential, it becomes necessary to go beyond the relief afforded by increased size of main. In such cases special conductors are run from the bus bars at the station to the point requiring a higher voltage supply. These lines are called *feeders*. They may originate with the same bus bars as the mains or they may come from buses of a higher potential by 10 or 20 volts.

Suppose that in the case already discussed feeders are run

from the bus bars of a few volts higher pressure than those from which the mains start and are connected at points I and N. The drop along these feeders may or may not be just enough to bring the voltage across IN up to that of AB. If it does we will have a potential gradient as shown in Fig. 174.

The feeders need not be run to opposite points of the system (that is, to corresponding points of the two mains) but may tap in at different parts. One such scheme much used combines with a directly fed main on one side an opposite main connected

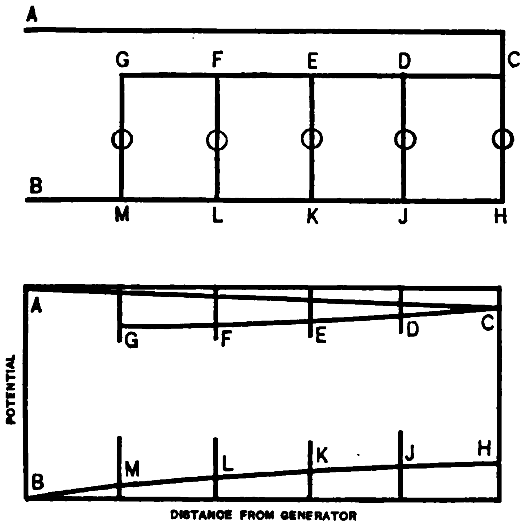


FIG. 175.—Potential gradient for extreme anti-parallel feeding points.

only at the further end by single feeder. This is called the *anti-parallel* system of feeding in contradistinction to the *parallel* system, just described.

A better regulation of voltage for the system can be obtained by feeding the mains in antiparallel fashion at points about midway between the ends and the centers (*i.e.*, at the quarter-way points). These two systems and their potential gradients are shown in Figs. 175 and 176.

Calculations.—The arrangement of mains each as a closed circle or loop with an antiparallel feeder system gives good regulation. The potential gradient for each half of the circuit

will be identical with that of the antiparallel system if loading is symmetrical. If this is not the case, we may illustrate the conditions by Fig. 177.

This gives a fairly complex case which will serve to illustrate numerous details in the calculation of such circuits. The assumptions made will be that the load is concentrated at four points of the loop in unequal quantities. At the quarter point EF, 20 amperes is used; at the five-eighths point GH, 80 amperes is used; at the three-quarters point JK, 40 amperes; at the seven-

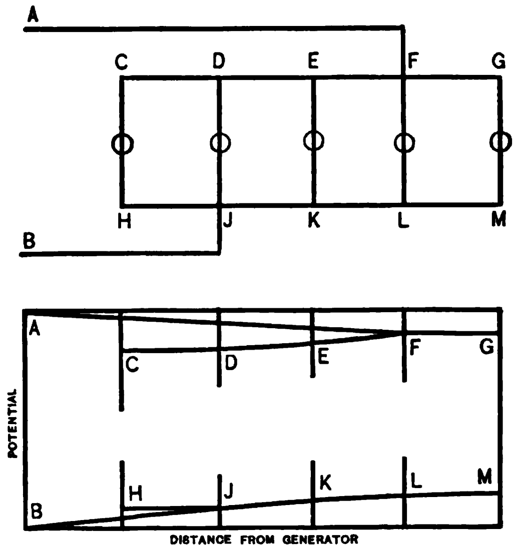


FIG. 176.—Potential gradient for intermediate anti-parallel feeding points.

eighths point LM, 40 amperes. Each main is assumed to have a resistance of 0.01 ohm per one-eighth of the loop, as LD, both mains being alike.

Inasmuch as the current in B will enter from the loop at D, where it is divided, part coming in each direction in the loop, it will be necessary for us in our calculation to distinguish between these two directions of flow. We may do this by assuming the clockwise direction in either main to be positive and the counter clockwise direction negative thereto. (This convention has nothing to do with the ordinary conception of positive and

negative terminals or mains but is merely an expedient to avoid adding two currents that may be opposed to each other.)

Considering the 20-ampere load at EF alone, it is evident that it returns over two parallel paths to B, one a short path DE, the other three times as long $DLJGXE$. The current will divide inversely as the resistances of these two parallel paths. There-

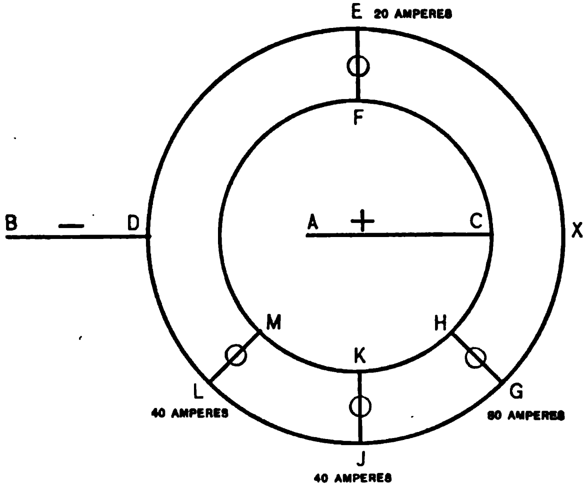


FIG. 177.—Unbalanced load on looped mains.

fore, 15 amperes will flow in DE in a negative direction (according to our convention) and in $EXGJLD$ there will be a current of 5 amperes flowing in the positive sense. These data are tabulated in the first row of Table XXI here shown, where the column headings indicate the sections of the mains being considered. Thus between D and E, -15 amperes flows; from E to G, $+5$ amperes flows; from G to J, $+5$ amperes flows, etc.

Table XXI.

	D — E	E — G	G — J	J — L	L — D
Load EF	-15	$+5$	$+5$	$+5$	$+5$
Load GH	-30	-30	$+50$	$+50$	$+50$
Load JK	-10	-10	-10	$+30$	$+30$
Load LM	-5	-5	-5	-5	$+35$
Current	-60	-40	$+40$	$+80$	$+120$
V. drop	-1.20	-1.20	$+0.40$	$+0.80$	$+1.20$

Similarly, the load of 80 amperes at GH would be returned, if alone, by two components 30 and 50 amperes. Therefore, the table shows D to E, -30 amperes; E to G, -30 amperes; G to J, $+50$ amperes; etc. Each one of the four parts of the load will be handled the same way. Then, summing the currents in each section of the main, we get the totals shown in row five of the same table.

By the known resistances, we find the drop in DE to be -1.2 volts ($e = ir = -60 \times 0.02$); in EG, -1.2 volts ($ir = -40 \times 0.03$); in GJ, $+4$ volts ($+40 \times 0.01$); etc.

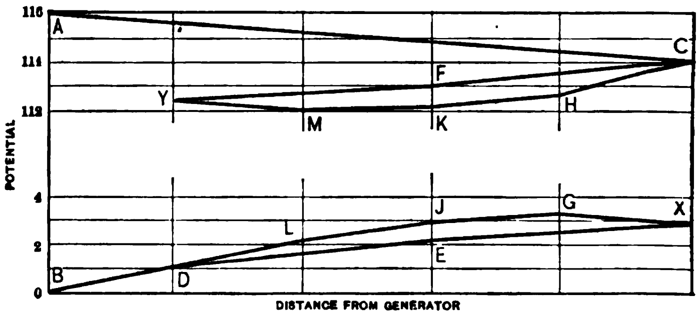


Fig. 178.—Potential gradient for unbalanced load on looped mains.

We now have in the last row of the table all the potential drops of the sections of this one main. Similarly, calculating the data for the other main, Table XXII presents the results.

In Fig. 178 are presented the results of both tables showing the potential gradient curve for the system.

Table XXII.

	C		F		M		K		H		C
Load EF		+15		−5		−5		−5		−5	
Load GH		+10		+10		+10		+10		−70	
Load JK		+10		+10		+10		−30		−30	
Load LM		+15		+15		−25		−25		−25	
Currents		+50		+30		−10		−50		−130	
V. drop		+1.0		+0.9		−0.1		−0.5		−1.3	

The feeder AC has not been calculated, but it is shown in the figure as having the drop indicated by the difference in level

between A and C. Similarly, BD is indicated. It is evident that M has the lowest voltage of all points upon the positive main, while G has the highest voltage of points upon the negative main. The lowest reading obtainable between the two mains will be from M to G. This reading will be less than that across any portion of the load. If there is 116 volts supplied to AB, and 1 volt drop in BD, and 2 volts in AC, the voltage supplied to the loops is 113 volts across CD. This gives the following readings of potential across the various members of the load:

$EF = 110.8 \ldots GH = 109.3 \ldots JK = 109.2 \quad LM = 109.9$, giving an extreme variation of 1.6 volts. The lowest voltage reading possible from M to G is 108.7 volts, being 0.5 volts less than that across any load unit.

Furthermore, considering B as zero potential, the points of the system have potentials:

B	0	A	116
D	1.0	C	114
E	2.2	F	113
X	3.0	Y	112.4
G	3.4	M	112.1
J	3.0	K	112.2
L	2.2	H	112.7

Altering the load at any point immediately disarranges these values. For example, suppose the load at JK to be thrown off. The totals representing current values in each section of the mains will be altered, becoming, in general, less, though in some cases there is an increase. The corresponding voltage drops will vary and hence the whole potential gradient will shift from what the figure shows in the assumed case. Such results are easily noticeable where lights are glowing when motors are supplied from the same lines.

Grounding a point on the system can place, at most, a voltage of 116 volts to ground. This would occur if either A or B is grounded. The reading would be maximum between ground and the ungrounded brush. The grounding of any other point upon the line will cause only slight differences from the above reading, 116 volts, because every point on each of the mains is

at nearly the same potential as one or the other of the bus bars. With lighting loads it is impossible to ground at the center of the lamp voltage, hence, any ground upon a two-wire lighting system may be considered as placing full potential between the other main and ground.

A very prominent instance of the above phenomena is obtained in connection with railway work. Here, not only does the amount of the load upon the line vary, but so also does the location of the load change. A car may be compelled to stop at each cross street, which will bring starting points every 200 to 400 feet. The grades will vary along the route as well as the loads upon the car. The car demands a heavy starting current or reduced running current. Thus, at intervals of a few moments the load represented by one car upon a system will vary from zero to maximum and to zero again, all the time changing its distance from the feeding point of the trolley wire. In parallel with this car there will be many more upon the system which are also unstable load units. With only a few cars the variations will be marked. With a greater number of cars running close together, the tendency is to even out the peaks and hollows of the load by superimposing upon the low places of one the high values of another. The lowering in the brilliancy of the incandescent lights of a car when it is starting indicates the change in voltage between the trolley wire and the rail due to heavy line drop because of the large starting current. The potential gradient of the system would show at that moment, not only a low point in the trolley wire voltage, but also a high point in the potential of the track return.

The distribution of the load once determined, it becomes a matter of design to find the drop in each portion of the line and the feeders. This presupposes an assumption of copper cross-section. Proper adjustments must be made then to bring the line drops within reason. The process may be reversed quite as well. We may allow certain line drops as maxima, then determine what the copper cross-section must be to give the proper resistance.

It is not necessary to have the mains of constant cross-section throughout their entire length. It is quite uneconomical to do so in many instances. By referring to the figures already shown,

it will be seen that in some places there are large currents while in others there are small currents. With the parallel system (Fig. 171) the mains at the outer end of the system will carry only enough current to supply one section of the load.

From the standpoint of cost of copper, it would manifestly be economical to decrease this main in size as the distance from the generator increases. In fact, better voltage regulation may be obtained by using at the beginning of the line some of the copper installed at the outer end of the line. If load units are large and are concentrated at different points, this amounts to decreasing the size of the conductor after each load is reached. With small, uniformly distributed units as lamps, etc., the limiting condition gives a tapering conductor. The engineering value of the latter type of installation is very low. The cost of conductor is high, and the end attained by its installation is of questionable value. Loads vary considerably from the estimated values. Patronage increases above initial conditions. Hence any carefully calculated system installed upon the basis of present estimate must be given a generous factor of safety before construction begins, with due allowances made for later increases. These needs enjoin the engineer from the use of costly conductors and the parabolic and conical conductors have earned no very high place in practice even in antiparallel systems where they establish uniform pressure at all points of the load. On the other hand, they may be approximated by using successive sections of cylindrical wires having different sizes.

This practice has its proper place in economical design. Even there, however, it is generally found undesirable to make the sections very short in order to allow for more uniform decrease in size.

Economy of copper is a very important consideration in the lay-out of any system of distribution. The voltage drop in the line varies as the current, being measured by *ir*. In order to transmit a given amount of power we may use low voltage and high current or high voltage and low current. In the first case we have a low voltage supplied and a heavy voltage drop due to large current. The voltage supplied at the load is much less than that generated and changes greatly with change of load. In other words, the voltage regulation is very poor.

In case of high voltage and low current, the *ir* product is low compared to the voltage generated and great changes in load may occur without serious change in voltage received by load. This may be applied to reduce the copper area while keeping the regulation as before, or the regulation may be bettered, letting copper cost remain high.

With ordinary incandescent lighting systems, the lamps require a pressure (nominally) of 110 volts. Actually, this value varies from 106 volts to 130 volts according to the system. Any great amount of load distributed at this voltage over a considerable distance would introduce very serious losses into the system as well as causing all regulation limits to be exceeded. It is, consequently, desirable to use a higher potential than 110 volts.

This requires that the lamps shall be put in series, which may be done by putting two 110-volt lamps across a 220-volt constant

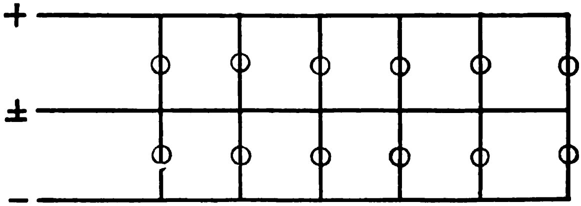


FIG. 179.—Fundamental three-wire system.

potential system. If one of these lamps is broken or needs to be cut out of the circuit, the other will not operate. In order to avoid this difficulty, there is installed a third wire connecting the midpoints of all pairs of lamps as is shown in Fig. 179. This wire must then return to the midpoint of the generator. The extra wire is called the *neutral* wire, and the generator terminal to which it is attached receives the same name, the neutral. This is the *three-wire system.*

If lamps are now installed in pairs and all are in operation, there will be no current in the neutral. When certain lamps upon one side of the system are turned off there is a current in the neutral. It may flow in either direction depending upon which side carries the heavier load. In fact, with unbalanced loads, it is quite possible to have a current in the neutral wire in one direction at one place, current in the other direction in another place, and no current at all elsewhere. The methods of genera-

tion for this system and the arrangements for securing the neutral will be discussed later.

With the load conditions assumed in Fig. 180 the potential gradient of the system is also illustrated. The load units are

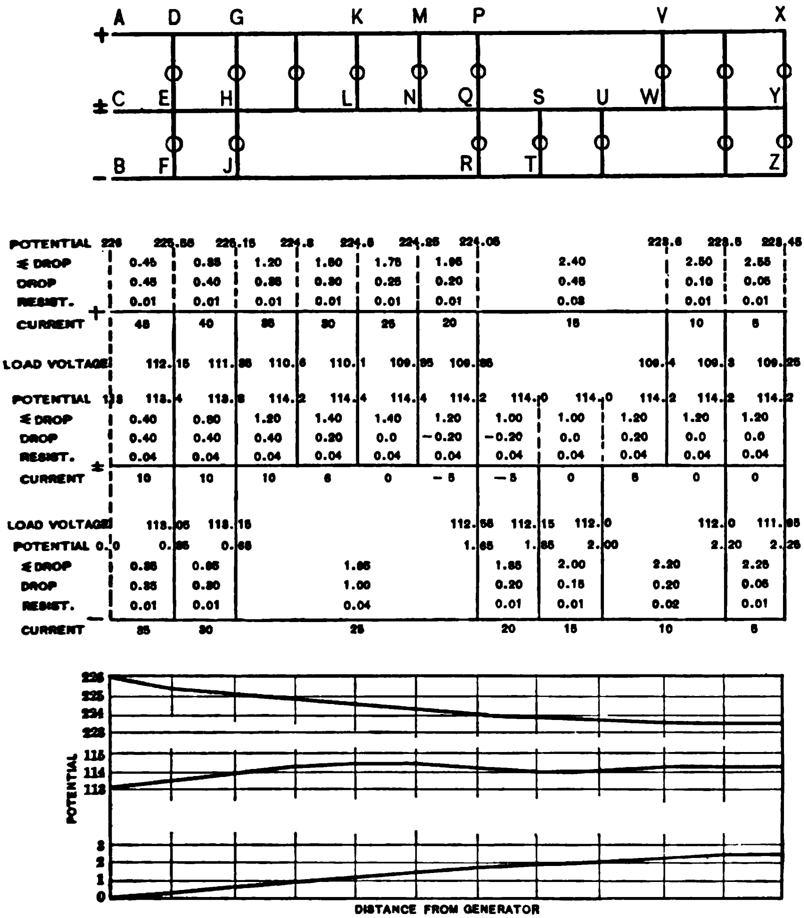


Fig. 180.—Loaded three-wire system and potential gradient.

assumed to take 5 amperes each. They are distant from each other a little less than 100 feet. The positive and negative mains are No. 0, B. & S. gage, which makes the resistance between load units approximately 0.01 ohm.

In order to determine the size of the neutral we will investigate the current carried by it with this arrangement of load. This may be done in either of two ways.

1. Beginning at the outer end of the mains, the last load unit between + and $\pm$, XY is balanced by YZ and may be considered in series with it. Therefore there is no return current in the neutral from Y. The next section is found to be similar. Load VW, however, has no corresponding load upon the opposite side. Its current must, then, return through the neutral to the next possible load, which is at U. Between W and U the neutral carries a current of 5 amperes. The next section carries no current. QS, however, must bring 5 amperes to the load ST. This current is in the opposite direction to that in WU, being *away from the generator*. It will be called negative, on that account, and it is supplied from PQ. Similarly MN will supply QR; KL will supply HJ; etc. This method is equivalent to pairing off the load units against each other, beginning at the outer end of the mains, and noting where current is present in the neutral and what its direction is.

2. Perhaps a more satisfactory way, in general, is to calculate first the currents in the positive and negative mains. This is a simple summation beginning again at the outer ends X and Z. As each load takes 5 amperes, successive sections of the mains will have current values increasing by this amount wherever load is supplied. From left to right upon the diagram, the mains will have in successive sections

5, 10, 15, 15, 15, 20, 25, 30, 35, 40, 45. Positive Main.
5, 10, 10, 15, 20, 25, 25, 25, 25, 30, 35, Negative Main.

But the differences between these readings must be present in the neutral wire. Subtracting the lower row from the upper row we have:

0, 0, 5, 0, -5, -5, 0, 5, 10, 10, 10. Neutral wire.

It is thus determined that the current in the neutral will be much less than that in either main. In fact, the high efficiency of the system demands that loads shall be as evenly balanced as possible, from which a low neutral current results. Practice varies the size of the neutral from one-quarter the size of the

other mains to one-half the size. A quarter-size neutral will give in the present case resistances of neutral equal to 0.04 ohms per section of about 100 feet.

We are now ready to calculate results by the use of a tabular form also shown in the figure.

Beneath each section of all three mains, in a diagram representing the system, is placed the value of the current therein as previously explained. Above each section is written the resistance of the section. The product of these two, *ir*, gives the voltage drop occurring in that section. Summing these drops for each line outwardly from the generator will give, in succession, the total drops to those particular points.

The negative brush *B*, may be taken as zero potential, which with 226-volt supply, will make the neutral 113 volts and the positive 226 volts.

Starting with 226 volts, the potential of the positive brush, *subtract* from it successively the summation drops along the positive main giving the potentials of all points along that main referred to the negative brush.

Starting with 113 volts, *add* to it, successively, the summation drops of the neutral (*added* because the conductor is considered as a *return*), giving potentials of points upon the neutral. Similarly, starting with zero and adding successively the summation drops of the negative main gives the potentials of points upon that main.

These three sets of potentials are plotted in the lower part of the figure, giving the potential gradient. There are given in the table the differences between these potentials which represent the load voltages.

Occasionally, the three wire system is added to, by putting two more wires in, making five wires in all with an outer potential of 440 volts. From the point of view of economy of copper, this is an improvement *when the load may be kept balanced.* The chief objection to it is that it is very laborious to arrange the load in the first place so that the neutrals carry little current, and even when this is done it is not likely to remain balanced. The same difficulty accompanies the use of three wire system except to a much lesser degree.

Grounding may occur in such a way as to give 226 volts

maximum to ground or only 113 volts maximum. The latter occurs if the neutral is grounded.

Feeders are conductors run from the station to points upon the mains, having the purpose of raising the voltage at the points of connection to the main and thereby throughout the whole vicinity. No load is ever directly attached to feeders. The combination of such lines is frequently spoken of as the *feeder and main* system. Feeders may originate at the same bus bars

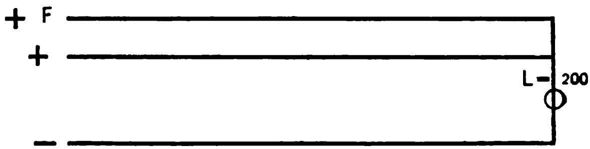


FIG. 181.—Simple feeder calculation.

as the mains or they may be fed from bus bars maintained at a higher voltage than the main bus bars. They may run in pairs or singly.

In the simple case of a single load upon mains as shown in Fig. 181, we may let

$L = 200$ amperes = load.
$r = 0.02$ ohms = resistance of main.
x = unknown = resistance of feeder.
$d = 1$ volt = allowable drop on one side of load.

Then $\dfrac{rx}{r+x}$ = resistance of main and feeder in parallel.

$$L\left(\frac{rx}{r+x}\right) = d = \text{the allowed drop in potential.}$$

Whence $x = \dfrac{dr}{Lr-d}$

Or, using the numerical values above given

$$x = 0.0067 \text{ ohms.}$$

As the main has a resistance of 0.02 ohms, this gives a feeder of three times the size of the main, by the installation of which the voltage drop at the load is reduced from 4 volts per main to 1 volt per main. That is, by increasing the copper cross-section to four times what it was before, we have reduced the drop to

one-quarter its original value. With a single load as above, this may be done by increasing the size of the main or by installing a feeder. The two schemes are very evidently identical. With intermediate loads, however, the two are not wholly identical. In order to show the effects of adding copper to the installation in different manners we will calculate the potential gradient for a system under several different conditions.

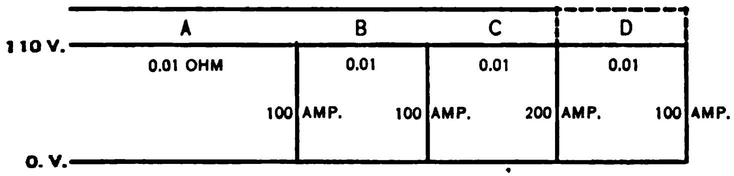


FIG. 182.—Feeder calculation with multiple load.

Four equidistant loads of 100, 100, 200, and 100 amperes, respectively, are separated by sections of mains having resistances of 0.01 ohm each. Figure 182 shows these data. Results will be tabulated for the 110-volt main with

1. No feeders.
2. 0.04 ohm feeder to last load point of line.
3. Doubled main to last load point of line.
4. 0.03 ohm feeder to next to last load point of line.
5. Double main to next to last load point of line.
6. 0.0225 ohm feeder to next to last load point of line.

It will be noted that the copper used in the feeder in each instance duplicates that of the main to the point indicated. Therefore, Nos. 2 and 3 use the same amount of copper, as do also Nos. 4 and 5. Number 6 uses for the shorter feeder an amount of copper equal to that used in No. 2.

Tabulating the calculations, we have as follows:

No. 1. No Feeders.

	A	B	C	D
Current	500.	400.	300.	100.
Drop	5.	4.	3.	1.
Σ drop	5.	9.	12.	13.

Potential 110........105.......101.......98......97.

No. 2. Full Length Feeders.

	A	B	C	D	F
Current	337.5	237.5	137.5	−62.5	162.5
Drop	3.375	2.375	1.375	−0.625	6.5
Σ drop	3.375	5.75	7.125	6.5	—
Potential	110......	106.625...	104.25....	102.875...	103.5.....

No. 3. Double Sized Main, Full Length.

	A	B	C	D	F
Current	500.	400.	300.	100.	None
Drop	2.5	2.	1.5	0.5	—
Σ drop	2.5	4.5	6.0	6.5	—
Potential	110.......	107.5.....	105.5......	104......	103.5.....

No. 4. Three-quarter Length Feeder.

	A	B	C	D	F
Current	300	200	100	100	200
Drop	3	2	1	1	6
Σ drop	3	5	6	7	—
Potential	110........	107.......	105.......	104.......	103

No. 5. Double Sized Main Three-quarter Length.

	A	B	C	D	F
Current	500.	400.	300.	100	None.
Drop	2.5	2.	1.5	1	—
Σ drop	2.5	4.5	6.	7	—
Potential	110.......	107.5....	105.5......	104.......	103.....

No. 6. Three-quarter Length Feeder, Large Size.

	A	B	C	D	F
Current	271.5	171.5	71.5	100.	228.5
Drop	2.715	1.715	0.715	1.	5.14
Σ drop	2.715	4.43	5.14	6.14	—
Potential	110......	107.3.....	105.6.....	104.9.....	103.9.....

Summarizing these tables and adding two columns showing the maximum drop in potential at the loads, we have Table XXIII.

Table XXIII.

Case.	Bus bar.	1/4	1/2	3/4	1	Maximum drop.	Variation at load.
1.	110	105.	101.	98.	97.	13.	8.
2.	110	106.625	104.25	102.875	103.5	7.125	3.75
3.	110	107.5	105.5	104.	103.5	6.5	4.
4.	110	107.	105.	104.	103.	7.	4.
5.	110	107.5	105.5	104.	103.	7.	4.5
6.	110	107.3	105.6	104.9	103.9	6.1	3.4

Without feeders the system will have upon it a variation in voltage at the lamps of 8 volts, which means a variation of 4 volts each way from the intermediate value, 101 volts, allowing the same drop upon the other main. This would not allow the

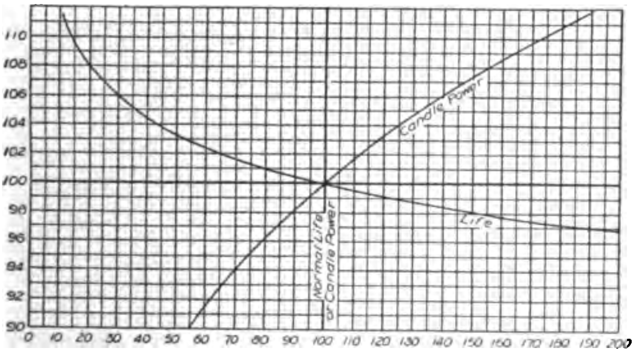


FIG. 183.—Relation of life and candle power of incandescent lamp to voltage regulation.

installation of lamps of one voltage rating upon the system for a variation of about 8 per cent. in voltage supply would change the candlepower by 40 to 50 per cent. The fact that there is a heavy line drop of 13 volts is not so serious as the one that the variation is enormous from point to point. On a lighting load we must design our circuit so that lamps in different localities will receive approximately the same voltage. The need of this is readily

seen by reference to Fig. 183, showing the variation in candle-power and life of a lamp with change of voltage across it.

A feeder equal to the main and running to the end thereof reduces the maximum drop to 7.125 volts, while the variation between load points is only 3.75 volts. The potential gradient shows a decided sag at the third load.

Conditions of Case 3 may be obtained from those of Case 2 by running jumpers from the feeder to the main opposite each load point. The result is to raise the potential gradient for the whole line except the end. Thus, while the maximum drop is less, the variation is greater than before.

Shortening the feeder, allowing it to reach only to the three-quarters point, and attaching it at no intermediate points gives no greater variation than did Case 3. The maximum drop is slightly greater. That is, with a saving of 25 per cent. in the copper of the feeder the regulation is just as good as Case 3 and only slightly poorer than Case 2.

Tying this shortened feeder in at each load point reached before its end gives a result similar to the previous case. Intervening voltages are raised but at the end of the feeder and beyond no change occurs. Naturally, the regulation suffers somewhat.

If, now, we take the amount of copper used in the long feeder of Case 2, extending to the end of the line, and concentrate it upon a three-quarters length feeder, we have a better result in respect to both regulations and maximum drop. The figures for this case are 3.4 volts variation and 6.1 volts maximum drop.

Before going farther, it should be noted that this calculation is for one main only, hence, with similar drop upon the opposite main we have a departure from normal of 3.4 volts across a set of lamps rated at the middle value. This still gives very large departures from normal candle-power and should be greatly improved in an actual installation. In this case, the mains should be enlarged and feeders installed as well.

Our comparative results still are representative, and it is seen that a certain amount of copper installed as a feeder gives better regulation over a system if it runs to a point other than the end of the main; that a feeder tied in to the main at successive load points will raise the average voltage of the system more than it will if attached only at its extremity, but this is done at the

expense of uniformity of potential. In general, these two points will determine the connections made from feeder to main.

In a lighting load, it may be necessary to raise the potential in a certain vicinity. This can then best be done by bringing a feeder to the point in question. Inasmuch as lighting circuits cover so great a territory and ramify so thoroughly throughout it, it will generally be possible to tie main circuits together at innumerable points, in which case, the lightly loaded mains will sustain the potential of the heavily loaded mains at some value intermediate to their individual potentials. Wherever possible, lighting mains should be thus tied into networks, as it tends toward increased stability of the whole system.

Feeders are still used in connection with networks, however, as they are the only means of relieving certain sections from the effects of overloads. They are then connected only at one point.

Railway loads differ in many particulars from lighting loads. Feeders paralleling the trolley wire are required for all such installations of any consequence. The load point is constantly shifting, however, and hence a feeder connected only at one point may be close to or distant from the place where the greatest relief is required. Moreover, the attempt is made to maintain as high voltage as possible under the bus bar potential at all points of the system. Mere uniformity of pressure is of no great importance, whereas high voltage throughout the system is important. Because of these several conditions, railway feeders should be tied to the conducting trolley wire at frequent intervals, the result being the same as if the trolley wire were increased in size.

Another difference between the two systems lies in the fact that, due to other causes than voltage regulation, it is impracticable to tie railway circuits into great networks as is done in lighting systems. Hence the paralleling of feeder and main by frequent ties is restricted in its application to limited circuits. Within the limitations allowed, however, it should be practised.

This restriction of networks is necessary in order to provide independence from local troubles upon the line. Disturbances are much more liable to occur upon a railway system than upon a lighting system due to the nature of the load, its fluctuations,

the more exposed line construction, etc., and when they do occur, they may be serious enough to entirely cripple all lines tied together by extending back into the stations. The greater the power represented in the network, the more disastrous may be the result of an accident. Even if sufficient protection is provided to avoid injury to apparatus, circuit breakers will open upon the lines and feeders represented, stopping cars and tying up traffic in all sections until the cause of the trouble is removed.

When feeders are to be installed to points upon a network, in order to find what size conductor is necessary in order to sustain

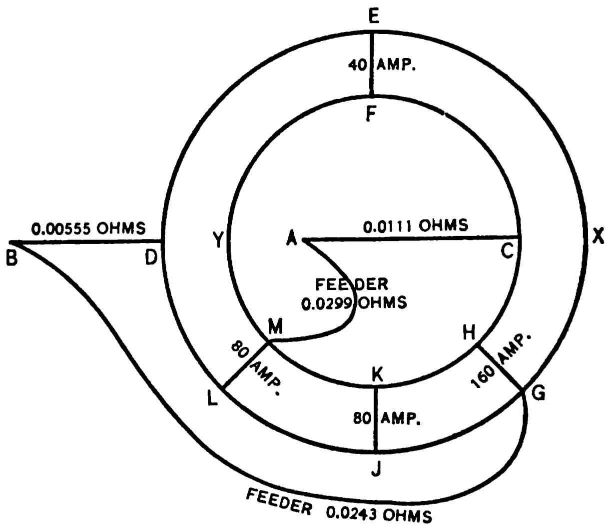


FIG. 184.—Feeders with looped mains.

potential at a given figure, we must know the resistance of mains or network to that point as well as currents and drops. Take, for example, the case of looped mains as shown in Fig. 177, with its potential gradient, Fig. 178. Suppose that due to the extension of service all loads are doubled in value. As currents are doubled, the drops are doubled. It is desired to keep the point M on the positive main at its original potential, 112.1 volts, it being the lowest point upon the gradient. Similarly, G is to be kept at its value, 3.4 volts. Consider M, G being handled similarly afterward.

The new conditions are represented by Fig. 184. Feeders are run from positive and negative buses to M and G, respectively. The resistance of the feeder AM will be such as to halve the drop which there would be without it. Therefore, its resistance must equal that of the old circuit A to M. This consists of $AC\left(r=\frac{e}{i}=\frac{2}{180}=0.0111\right)$ is series with the two parallel paths CFM ($r=0.05$) and $CHKM$ ($r=0.03$). Whence the circuit resistance equals

$$0.0111+\frac{(0.30)(0.05)}{0.30+0.05}=0.0299 \text{ ohms.}$$

This will be the resistance for the feeder AM. We now have a network of conductors such that there are four possible circuits for current to follow in passing from A to K, H or F. This gives a rather tedious calculation of current division derived by inverse resistances.

We find, however, that the current and drops in different portions are:

	A	*C*	*F*	*M*	*K*	*H*	C *A*	*M*
I.	224.8	−49.3	−9.3	−64.5	15.5	175.5	—	135.2
Drops	2.5	− 0.986	−0.279	− 0.645	0.155	1.755	—	4.00

This gives potential gradient as compared with the former condi-

	A	*C*	*F*	*Y*	*M*	*K*	*H*
New	116	113.5	115.0	113.1	112.2	111.6	112.4
Old	116	114	113	112.4	112.1	112.2	112.7

tion where the two values for M, 112.2 and 112.1, are identical except for small errors in the calculations. It will be noted that, whereas the old condition gave potential variation at the loads of 1.9 volts, the new arrangement gives 3.4 volts' variation upon this one main. Without calculating the gradient of the other main we cannot tell what effect this will have upon load voltages, or how great will be their departure from a midvalue.

As before noted, the feeder upon a 110-volt system may come from a bus bar which has a potential of 112 volts. In this case the feeder will not need to be so large in order to give the same relief.

Take, again, the case shown in Fig. 181 and discussed on p. 216. With the feeder coming from the 110-volt buses it was found that it would be necessary to install a feeder three times the size of the main in order to permit a drop of 1 volt per main. If the feeder is derived from a 112-volt bus bar we will have the conditions shown in Fig. 185.

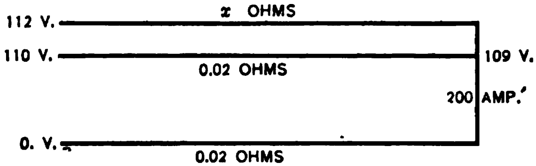


FIG. 185.—Feeders from auxiliary bus bars.

There will be allowed a drop of 1 volt in the main. Its current must, therefore, be

$$i=\frac{e}{r}=\frac{1}{0.02}=50 \text{ amperes.}$$

This leaves 150 amperes to be carried by the feeder. But the feeder will have 3 volts drop (112–109). Its resistance will, therefore, be 0.02 ohms. But this is the same as for the main. Hence, if the feeder originates at a 112-volt bus bar, it may be of the same size as the main, or only *one-third* what was required for the other case. Or the total amount of copper used, mains and feeders, would be 50 per cent. less with the higher voltage feeder. Upon this plan, the corresponding auxiliary bus bar for the negative feeder would be at a potential of -2 volts. This may be extended into network calculations and a decided saving in copper will be shown in conjunction with the use of higher voltage feeders. This leads to the installation of *auxiliary bus bars* at stations, practice including sometimes three or four steps in potential. The lowest of the auxiliary buses are used upon smallest loads and shortest distances, reserving the highest voltage for long or heavily loaded feeders. Typical steps would be represented by pressures of 110, 114, 118, 122 volts between pairs of buses. These would be so arranged that successive positive buses would represent potential differences of 2 volts, successive negative buses being similarly spaced. The same arrangement will apply to alternating current distribution,

although we must there refrain from distinguishing between buses by the use of algebraic signs.

While the design of mains and feeders is extremely simple having once determined the allowable power loss or the voltage drop, the determination of that starting point is far from elementary. It will take but a little work to determine that a feeder must be of such and such a size in order to bring voltage regulation within certain desirable limits. This, however, does not finish the investigation, which must be carried far enough to indicate the expense for the proposed scheme and the saving accomplished by it, reduced to the annual basis. The economical design of the system may be quite a different thing from that needed for certain ends. A proposed improvement may not pay for itself. With networks of conductors or even with simple circuit conditions the ultimate solution is very complicated.

The first promulgation of anything like a general law covering this determination is known as "Lord Kelvin's Law." Briefly it may be stated thus: *The most economical conductor is that one for which the annual interest upon capital invested will equal the annual cost of energy wasted.*

This "law" has been revised and extended in very many particulars, yet it is of doubtful value, except in a most general sense or an *entirely* specific case. But the latter is never found. The solution contemplates the cost of conductor, whereas, line incidentals vary in connection with conductor changes but not in the same ratio. These ratios are hard to determine and can be expressed only approximately. An investment once made in line material and construction represents a fixed charge in interest, maintenance, etc. In the meantime, the power loss will vary with the load carried and may either increase or diminish. The *cost of energy wasted* may be considerably less than the *value* of that energy, considered from the commercial standpoint, provided there is a demand for all the power available. Even then, we are not so much interested in the cost of power or of the price for power as we are in the margin between these two, which represents earnings. The financial problem must contemplate the frequent necessity of low first cost in order to allow any kind of a start to be made without imposing too large a burden of fixed costs before returns will warrant them or backing can be

secured to satisfy them. This is a very common condition imposed upon the engineer. It carries with it the necessity for future extensions and enlargement after initial success has been attained.

If all the very numerous conditions going to make up the problems of design were similarly effective in the various propositions, this method would be of much assistance. Or, if similar cases could be successfully grouped, there might be warrant for its use. But power systems are individual, and classification by certain standards will accomplish little when analysis begins.

In general, where railway, lighting, or power distribution circuits are concerned, and indefinite amounts of power are used, it is advisable to assume in design a definite line loss unless power supply is closely limited. This loss will vary from 4 or 5 per cent. for short distances to 15 or 20 per cent. for long distances. The larger losses would indicate ample source of inexpensive power, as water-power. If, upon the other hand, the power is purchased and the system contemplates distribution only, economy of handling is desirable, as it is seldom known in advance what the marginal difference will be between purchase price and selling price. If this were known, it would allow check calculations to be made balancing value of lost power against fixed charges accompanying increased price of construction.

This needs one more point of advance information in order to become fairly secure. That is the amount of power used. Here, if power is purchased, small loss and small cost of installation must be balanced against each other. Wherever there is a limited source of power with a generous demand for practically all that can be furnished, low line losses are desirable.

Reliability of service is a consideration which often very seriously affects the design, increasing cost in many cases by serious amounts. It is, of course, necessarily accompanied by increased difference between cost price and selling price. Situations are numerous where this phase of the subject is of paramount importance and all other considerations give place to it.

For distributing circuits for combined light and power, Dr. Steinmetz, in his "General Lectures," reaches the following conclusions in regard to copper economy.

1. Two-wire direct-current or single-phase alternating-current

110-volt circuit, used for short distances only, may be used as the standard of reference and therefore uses 100 per cent. of copper.

2. Three-wire direct-current or single-phase alternating-current 110–220-volt circuit, with neutral at half size outer mains will use 31.25 per cent. of copper.

3. Four-wire quarter-phase alternating-current circuit, each phase being 110 volts, copper used is 100 per cent.

4. Three-wire quarter-phase alternating-current circuit, each leg 110 volts, with common wire 1.41 times the size of outer mains, uses 72.9 per cent. copper.

5. Three-wire, three-phase alternating-current circuit, line voltage, 110 volts, uses 75 per cent. of copper.

6. Five-wire, quarter-phase alternating-current circuit, with 110 volts between each line and neutral, with neutral of one-half the size of each outer main, copper used is 28.125 per cent.

7. Four-wire, three-phase alternating-current circuit with 110 volts from each line to neutral, with neutral half the size of each outer main, uses 29.17 per cent. of copper.

8. Four-wire, three-phase alternating-current circuit, with 220 volts between mains, with neutral placed between two lines only forming a 110-volt, single-phase lighting circuit with a 220-volt three-phase power circuit, uses 31.25 per cent. of copper, for lighting, but only 18.75 per cent. for power.

Summarized, these may be illustrated by Fig. 186. Number 2 is most frequently employed with its very low percentage of copper, 31.25 per cent. Number 8 is practically the same thing except that an additional wire is used to give three-phase power. This will permit the installation of polyphase motors upon the line, while No. 1 will allow only single-phase units.

It will be noted that, wherever the distribution can be described as an approximately double voltage system, economy is marked. Numbers 2, 6, and 8 are at 220 volts. Number 7 is at 190 volts; these save considerable copper. Number 6 has five conductors, however, which means a greater cost of installation and maintenance.

In the foregoing discussions, we have assumed certain conditions of supply without indicating how these particular relations of voltages, etc., are ordinarily secured.

For example, the three-wire system has been mentioned,

wherein, with either direct current or alternating current, the distribution voltage is at double the potential used by the lamp unit and a third wire, called the neutral, is installed, being of a potential midway between the two main conductors.

With alternating current, this end is very easily attained, as it is a simple matter to bring a middle tap out of a transformer secondary, to put two transformer secondaries in series, with the neutral coming from their common point, or even to bring a

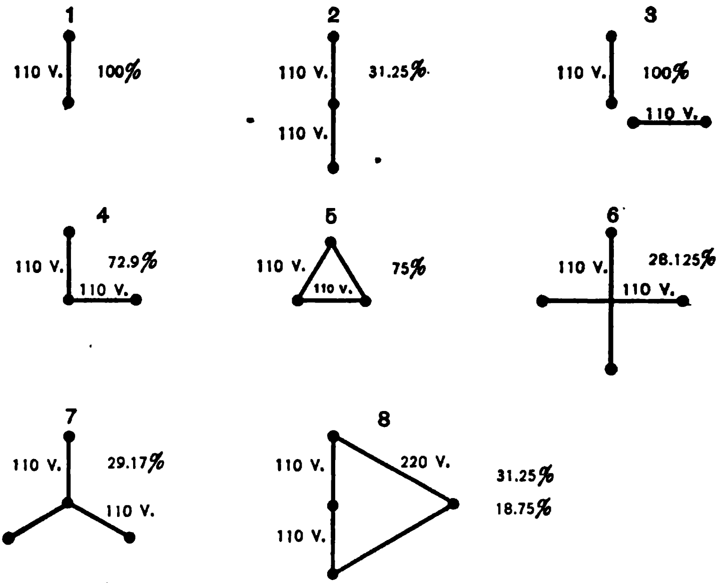


FIG. 186.—Copper economy for various systems of distribution.

middle tap from the generator, if only short distances are served. Ordinarily, of these three conditions (*a*) (*b*) and (*c*) of Fig. 187, the first one is most commonly seen. The distance from generator to transformer may be several miles if desired, and the voltage used for this two-wire distribution may be high enough to give economy of construction. If long distances are necessary it is best to transmit by high voltage three-phase circuits separating phases and using lower potential, as 2300 volts, from substations to local transformers placed upon poles and changing to 220 volts with 110-volt neutral.

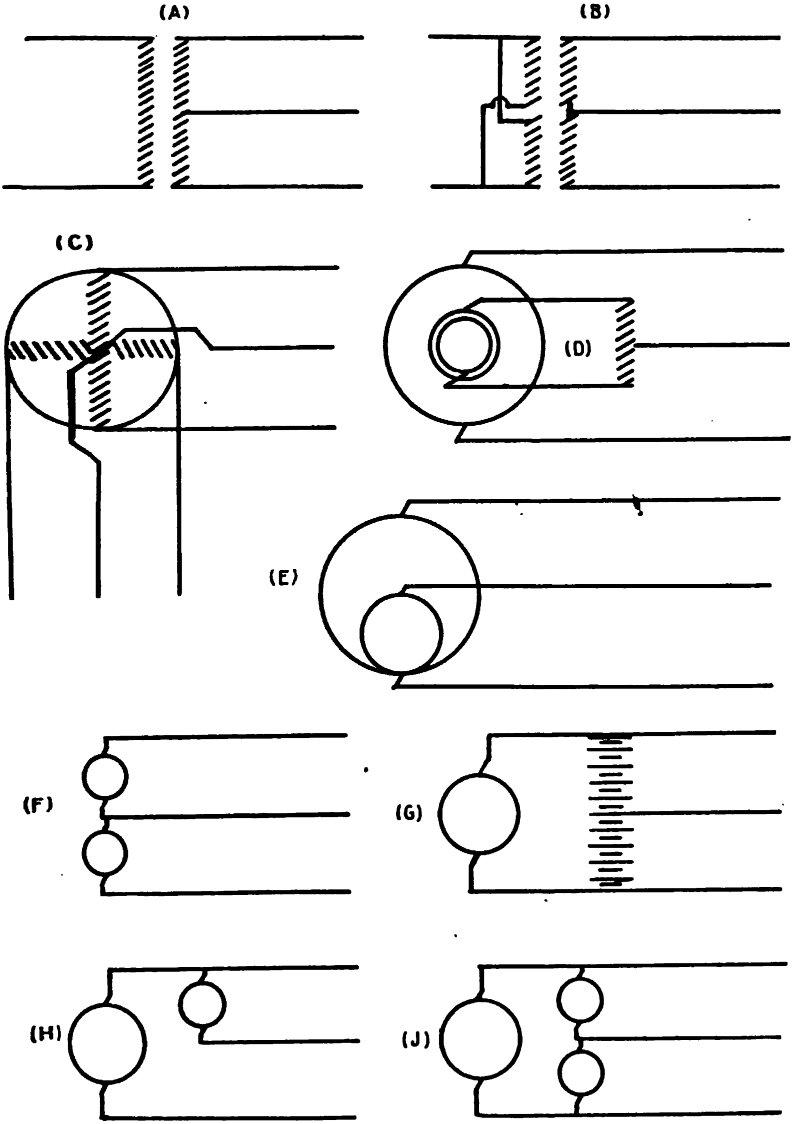


Fig. 187.—Sources of supply for three-wire system.

With direct current the matter is not so simply arranged. In order to bring out the neutral of an armature winding used with commutator and brushes, it is customary to arrange circuits as shown in (*d*) Fig. 187. This *three-wire generator* has two slip rings diametrically connected to the armature winding. A reactance coil is placed across the circuit from the center of which the neutral may be taken. Another way of securing this is by placing upon the armature an auxiliary winding of half the number of turns and permanently connecting it to the main winding at one point (*e*). The point upon the secondary winding

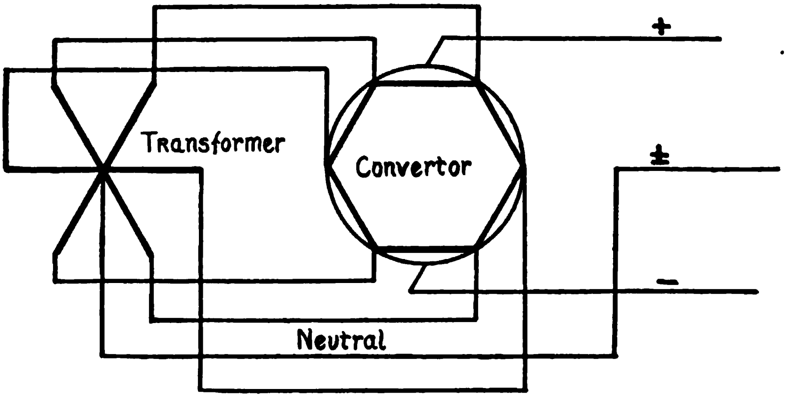


Fig. 188.—Bringing a direct-current neutral from a transformer.

diametrically opposite to the point of connection is the neutral point of the armature. One lead coming out to one slip ring will give this neutral connection and no reactance coil is required.

Two generator armatures placed in series (*f*, Fig. 187) is, perhaps, the simplest scheme used.

One generator with a storage battery floating across the line will allow a neutral to be brought out of the midpoint of the battery *g*, Fig. 187. An auxiliary generator may be used between one line and neutral (*h*), where it will operate as generator when its side of the system is overloaded, but will run as motor when the other side carries the overload. Its driver should be arranged to pump back upon the line. This may be done by belting it to the main generator, or, as is quite frequently done, the motor may be similarly installed between neutral and

the other main. This (*j*) is known as a *balancer set*, and the motor and generator relationship will change between the two members of the set with a shifting of maximum load from one side to the other of the system.

When rotary convertors are used to give 500 volts direct current for railway work, it is frequently desirable to secure 250-volt circuits for light workshop motors, etc. This may be done by bringing a neutral wire from the center of the transformers supplying the rotary convertor. This point is of exactly the same potential as the neutral point of the armature winding

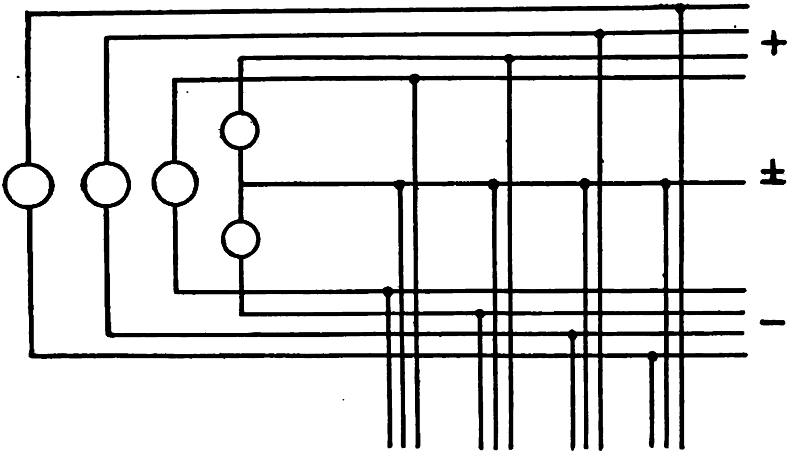


FIG. 189.—Auxiliary generators with three-wire system.

would be if such a point actually existed. The diagrammatic sketch of Fig. 188 will make this relationship clear.

Numerous other less common schemes exist, using combinations of boosters, balancers, etc. When auxiliary bus bars are to be used for sending out long feeders, it is usual to install additional generators. This is illustrated in Fig. 189.

CHAPTER VIII.

CONSTANTS OF CIRCUITS.

Resistance.—All material used for conductors present *resistance* to the flow of energy. This property of conductors has already been discussed in the first chapter. There we found copper to be the best material commercially available, as it has the lowest resistance. Owing to lightness of aluminium this metal stands a close second in choice, though its resistance is considerably more.

The resistances noted in that discussion, however, are the true ohmic resistances, values which may be observed with the use of direct currents, and they are the causes of the heating of the conductors. That is, because of the resistance, it requires the expenditure of energy to transmit power and this energy loss is measurable.

We have, then,

$$r = \frac{p}{i^2} = \frac{e}{i}.$$

Either means suggested by this formula may be used in the determination of the resistance, the measurement of power loss and current or the measurement of voltage and current. This assumes no leakage current, or, at least, by neglecting to correct therefore, one includes the leakage path as a part of the circuit measured.

Alternating current may not be used in this reading unless other restrictions are made.

With alternating current flowing in a circuit, there is an alternating flux set up around the conductor. This flux cuts adjacent materials during its alterations and there results therefrom an induced voltage in the substance. This will cause to flow a load current, in quantity depending inversely upon the resistance of the path of flow. A corresponding loss is introduced due to these *secondary currents.*

There is likewise an energy loss in the power required to reverse the magnetism of iron (or other material) in the immediate vicinity of the circuit. This *hysteresis loss* also uses power from the circuit.

Unequal current distribution, especially noticeable with the use of iron conductors, gives the effect of smaller cross-section of wire. This gives a similar, though small effect, with large copper conductors and in every case is greater with increased frequency of alternations.

Here, then, are those additional sources of loss of energy which will be included in the reading of power loss. Hence, in designating the *resultant resistance of the circuit* as in opposition to the *true ohmic* resistance, we use the term *effective resistance,* because the circuit has the same effect upon current flow as if it had this particular ohmic resistance without other losses.

It must be remembered, therefore, that the effective resistance of a circuit will exceed the ohmic resistance by an amount depending upon the hysteresis loss, eddy current loss, unequal current distribution, etc. The general nature of the circuit will tell whether or not the effective resistance will be appreciably different from the ohmic resistance. For example, in an aerial transmission line the hysteresis losses in dielectrics, the eddy current losses in conductors, the skin effect, etc., total only a very small percentage of the whole resistance and are generally neglected in calculating the circuit.

The self induction between wires carrying alternating current depends upon dimensions as may be seen by the formula for the *coefficient of self induction.*

Unit current flowing in a circuit sets up a certain field of force about the conductor. The *coefficient of self-induction* is the number of lines of force interlinked with the circuit per unit current.

For all practical purposes, sufficient accuracy may be attained in its calculation by making certain approximations. It will be assumed that the conductors are distant from each other far enough so that the radius of the conductor is small compared with the interaxial distance; that current distribution in the conductors is uniform; that in integrating flux from one conductor to the other by proceeding to the center of the second wire we have

averaged the effect of that flux cutting the second conductor; that permeability of the surrounding medium is unity. For cables at short distances from each other these assumptions cannot be made with impunity.

Figure 190 gives the conditions of the circuit.

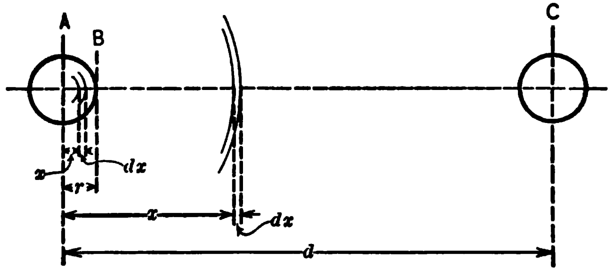


FIG. 190.—Calculation of coefficient of self-induction.

Flux in any elemental shell dx, of radius x, from A to B is set up by that portion of the current within the shell. This current is only a portion of the total current I.

$$i_x = \frac{x^2}{r^2} I.$$

It exerts a magnetomotive force in the annular zone dx amounting to $\frac{x^2}{r^2} I$ centimeter-gramme-second units, the path being $2\pi x$ in length. Hence, the magnetomotive force per unit length of path is

$$\frac{x^2}{r^2} I \div 2\pi x = \frac{xI}{2\pi r^2} \text{ c. g. s. units.}$$

The flux produced in the cylindrical shell of thickness dx is

$$4\pi \left(\frac{xI}{2\pi r^2}\right) dx = \frac{2xI}{r^2} dx.$$

This flux, however, does not represent an equivalent number of interlinkages, because it surrounds only $\frac{x^2}{r^2}$ of the conductor and its current. Therefore, we have

$$\frac{2xI}{r^2} dx \left(\frac{x^2}{r^2}\right) = \frac{2x^3 I}{r^4} dx \text{ interlinkages.}$$

The limits of integration for this condition are $x = o$ and $x = r$, beyond which, conditions change.

$$\frac{2I}{r^4}\int_o^r x^3dx = \frac{2I}{r^4}\left(\frac{r^4}{4}\right) = \frac{I}{2}, \text{ interlinkages within conductor.}$$

Beyond the surface of this conductor the magnetomotive force per unit length of path is $I \div 2\pi x$. The resulting flux will be, for width dx,

$$\frac{I}{2\pi x}\left(4\pi\right)dx = \frac{2I}{x}dx.$$

The limits, as stated in our assumed conditions, will be $x = r$ and $x = d$, counting to the center C of the opposite wire.

$$2I\int_r^d \frac{dx}{x} = 2I \log_e \frac{d}{r}.$$

This flux interlinks with the total wire so that we have interlinkages:

$$\phi = \frac{I}{2} + 2I \log_e \frac{d}{r}.$$

Whence the coefficient of self induction per unit length of conductor is

$$L = \frac{\phi}{I} = \frac{1}{2} + 2\log_e \frac{d}{r}, \text{ c. g. s. units.}$$

$$L \text{ per cm. of wire} = \left(0.5 + 2\log_e \frac{d}{r}\right)10^{-6} \text{ millihenrys.}$$

The presence of the natural logarithm in the formula necessitates the use of a reduction constant with common logarithms, hence, if

log is to base 10.
d = distance between centers of two conductors.
r = radius of conductors.
L = self inductance of each conductor in millihenrys.

We have

$$\left(0.5 + 4.61 \log \frac{d}{r}\right)10^{-6} = L \text{ per centimeter.}$$

$$2.54\left(0.5 + 4.61 \log \frac{d}{r}\right)10^{-6} = L \text{ per inch.}$$

$$30.48\left(0.5+4.61 \log \frac{d}{r}\right)10^{-6}= L \text{ per foot.}$$

$$30480\left(0.5+4.61 \log \frac{d}{r}\right)10^{-6}= L \text{ per 1000 feet.}$$

$$160930\left(0.5+4.61 \log \frac{d}{r}\right)10^{-6}= L \text{ per mile,}$$

$$\text{or } 0.0805+0.741 \log \frac{d}{r} = L \text{ per mile.}$$

When a three-phase circuit is considered with conductors at vertices $a.b.c.$ of an equilateral triangle, the flux set up by current in any one conductor does not pass between the other two conductors. That is, the inductance of ab is not affected by c. However, b does not carry all of the return current for a besides which it does carry some return current for c. The current cycle in a is the same as that for b except for the phase.

The self inductance of a will be as before determined for one conductor of a single-phase circuit, because we may consider the

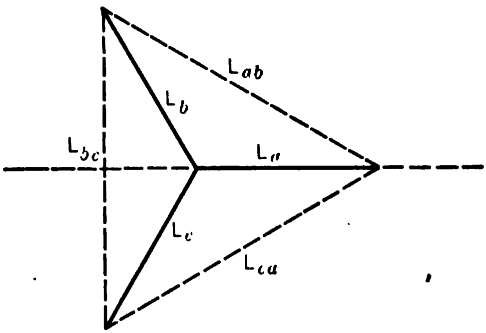


FIG. 191.—Self-induction of three-phase circuit.

single conductor a with return circuit at b and c both wires distant d. Similarly, the self inductances of b and c are the same amounts, but the effects do not add directly, because of the phase differences in the currents. In fact, the familiar Y vector diagram will be of use in understanding the conditions. Considered as individual conductors (that is, positive outwardly from the same end and not as returns) they differ in phase by 120°.

In Fig. 191 the vector L_a represents the self-inductance of conductor a per mile and is equal to

$$L_a = 0.0805 + 0.741 \log \frac{d}{r}.$$

Similarly, L_b and L_c have the same values, but are combined with L_a and each other at angles of 120°. The inductance of the loop ab is, therefore, the vector difference between L_a and L_b (*difference* because they are not considered as return conductors). Similarly for bc and ca, whence

$$L_{ab} = L_{bc} = L_{ca} = \sqrt{3}\left(0.0805 + 0.741 \log \frac{d}{r}\right).$$

When a two-phase, four-wire system is used, if the four conductors are located at the corners of a square the two phases may be considered separately. The inductance per mile of conductor is, as for the single-phase circuit,

$$L = 0.0805 + 0.741 \log \frac{d}{r}.$$

Per phase of two wires the value is twice this. Per circuit of two phases, the phase inductance is divided by two, reducing the value to the same as for one line.

Subdivision of a conductor is often said to decrease the inductance. This is an error caused by confusion of the ideas of inductance and inductive drop. By examining the formula for the value of L it will be readily seen that decreasing r will increase L, the direct opposite to the above statement. The effect upon inductive drop, however, may be to lessen it. With an alternating current circuit, the voltage drop due to self induction is measured by the rate of cutting of the lines of force through the conductor loop. Reduced to volts, the expression becomes $Ix_L = 2\pi fLI$ where L is measured in henrys and f is frequency. The quantity x_L is called the reactance and equals $2\pi fL$. Whence it is seen, that by dividing each of the conductors and *separating the two circuits* far enough so that they have no mutual effect, while x_L increases slightly for each line, the product Ix_L will be little more than half the former value, because I is halved for each circuit. Subdivision of conductors increases the self

inductance of the circuits but separation of the circuits will decrease the voltage drop. Consequently, where inductive line drop is excessive due to low voltage and heavy current, the installation of two or more parallel lines is advisable.

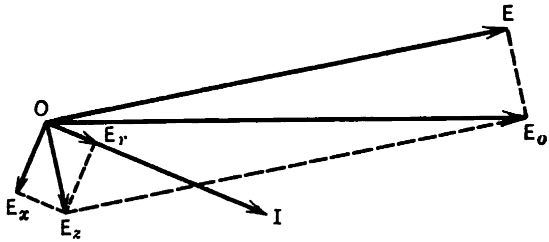


FIG. 192.—Line drop, single-phase.

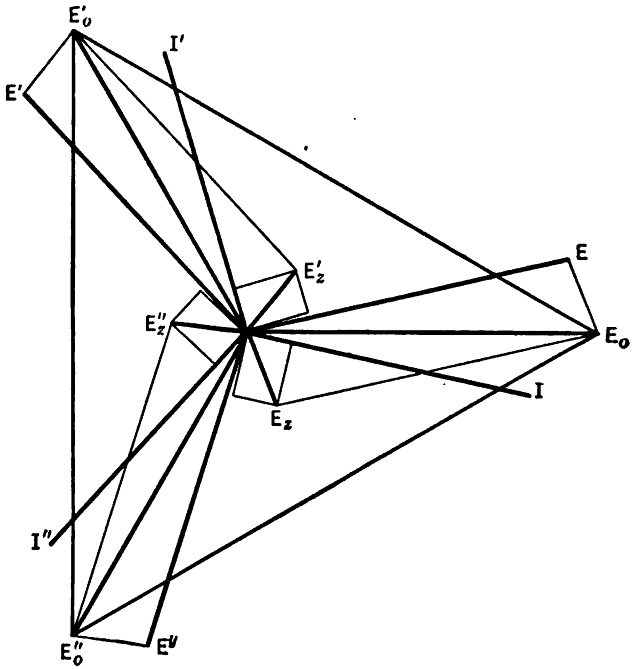


FIG. 193.—Line drop, three-phase.

The inductive drop upon the line is combined with resistance drop at right angles. To illustrate, in Fig. 192 there is shown E_o, the generator voltage, with I, the current supplied at an angle α

in advance. The drop due to resistance requires a supply in phase with the current, $Ir = E_r$, while the drop due to reactance requires a supply in advance of the current by 90°, $Ix_L = E_x$. These two add to $Iz = E_z$ where $z = \sqrt{r^2 + x_L^2}$. It is seen, then, that the drop due to the impedance z will be the cause of subtracting from the generator voltage the vector E_z, leaving E as the supplied voltage at the receiver end of the line.

Figure 193 shows a similar condition for a three-phase circuit. The line voltages at the generator are represented by the sides of equilateral triangle E_0, E_0', E_0''. The receiver voltages are similarly indicated by the triangle E, E', E''.

Capacity.—The two wires of a circuit maintained with a potential difference between them induce charges upon each

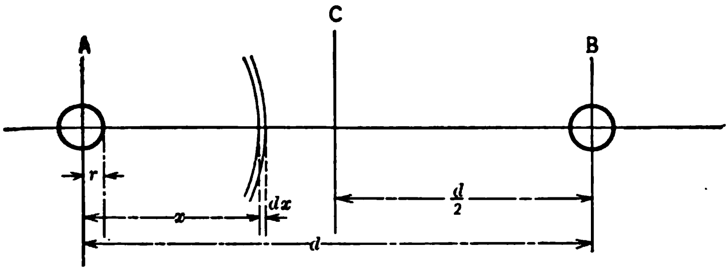


FIG. 194.—Capacity of single-phase line.

other. The *capacity* of the line is the ratio of the charge upon the line, to the potential causing the charge. Or, what is the same thing, it is a measure of the quantity of electricity held by the line when it is charged to unit potential.

It may be calculated or measured. For normal transmission lines we may assume that the charge is uniformly distributed over the conductor. This will not hold for wires or cables placed close together. Assume two conductors of a circuit as having (Fig. 194).

r = radius of conductor.
d = distance between centers of conductors.
x = distance from center of one conductor to some point between the two wires.
Q = the charge upon each wire, negative for B, positive for A.
k = Specific ind. cap. and is assumed to be that for air = 1.0.

The electrostatic field about the conductor A due to its charge will have a value $4\pi Q$, while at a distance x from the line its intensity will be

$$\frac{4\pi Q}{2\pi x} = \frac{2Q}{x}.$$

The electrostatic field at the same point due to the charge $-Q$ upon B will be measured by

$$-\frac{4\pi Q}{2\pi(d-x)} = \frac{-2Q}{d-x}.$$

The resulting intensity is

$$\frac{2Q}{x} + \frac{2Q}{d-x}.$$

The potential obtained by a particle moving from the center plane C, which is at zero potential, to the surface of the conductor A will be the same as that of the conductor.
The potential is

$$\int_r^{\frac{d}{2}} \left(\frac{2Q}{x} + \frac{2Q}{d-x}\right) dx = 2Q \left[\log_e x - \log_e (d-x)\right]_r^{\frac{d}{2}}$$
$$= 2Q\left(\log_e \frac{d-r}{r}\right).$$

Charge for unit potential will, therefore, be

$$C = \frac{Q}{2Q\left(\log_e \frac{d-r}{r}\right)} = \frac{1}{2\log_e \frac{d-r}{r}}$$

Again, where d is large compared to r, $d-r$ may be considered as equivalent to d. Hence, we may for ordinary aerial lines, use

$$C = \frac{1}{2\log_e \frac{d}{r}} \text{ electrostatic units.}$$

If we change our system of units to the electromagnetic units and let

C = capacity in microfarads of one conductor in respect to the neutral plane,

$d =$ interaxial distance between conductors,
$r =$ radius of wire,
logs are taken to base 10,
then,

$$\frac{0.241}{\log \frac{d}{r}} 10^{-6} = C \text{ per cm. of wire.}$$

$$\frac{0.613}{\log \frac{d}{r}} 10^{-6} = C \text{ per inch of wire.}$$

$$\frac{7.36}{\log \frac{d}{r}} 10^{-6} = C \text{ per foot of wire.}$$

$$\frac{7360}{\log \frac{d}{r}} 10^{-6} = C \text{ per 1000 feet of wire.}$$

$$\frac{38780}{\log \frac{d}{r}} 10^{-6} = C \text{ per mile of wire.}$$

$$\text{or } \frac{0.03878}{\log \frac{d}{r}} = C \text{ per mile of wire.}$$

The capacity of the *circuit* (consisting of two wires) for each of these respective lengths will be half the above quantities, as we may consider that there are two line-to-neutral capacities placed in series across full potential. Hence, we may consider the line as having a *certain capacity per line referred to line-to-neutral voltage* or as having *one-half that capacity referred to line-to-line voltage.*

With a three-phase, three-wire system, the capacity of each wire to neutral is represented by the formulæ as above given for line-to-neutral with two wires. The distance between wires is still given as d. That is, the equilateral triangle is of side d. This may be proven analytically or it may be shown by the following process of reasoning.

In Fig. 195 is shown a three-phase line with wires at A, B, and C. The radius of each wire is r and the axial distances between them d.

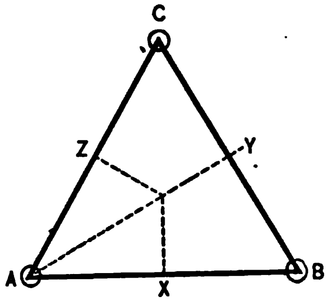


FIG. 195.—Capacity of three-phase circuit.

Considering two wires, A and B, the line-to-neutral capacity of A would be, per mile of conductor,

$$C_{ax} = \frac{0.03878}{\log \frac{d}{r}}.$$

The capacity of A to neutral Z will similarly be

$$C_{az} = \frac{0.03878}{\log \frac{d}{r}}.$$

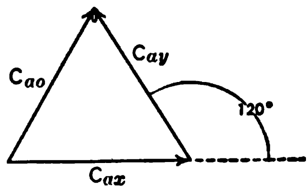


FIG. 196.—Vector sum of capacity.

These two capacities are in parallel but are not effective in time phase with each other. In fact, they must be added vertorially at 120° displacement because that is the displacement between the electrostatic stresses between the two phases. This gives Fig. 196, where as vectors

$$C_{ao} = C_{ax} + C_{az}$$

But C_{ao} is *numerically* the same as C_{ax} or C_{as}, etc.
Therefore

$$C_{ao} = \frac{0.03878}{\log \frac{d}{r}}$$

This gives the line-to-neutral capacity of each line, across which line-to-neutral voltage is impressed.

An infinite capacity would act like a short circuit upon the line, as is shown by the formula for the reactance due to capacity,

$$x_c = \frac{1}{2\pi f C}$$

The reactive drop in voltage is

$$I x_c = \frac{I}{2\pi f C},$$

and is negative in comparison to the inductive reactance. Thus we have for the total reactive drop, due to both inductance and capacity in the same circuit,

$$E_x = I(x_l - x_c) = Ix.$$

The resultant of the two adds to resistance drop at right angles, giving for impedance drop

$$E_z = I\sqrt{r^2 + (x_l - x_c)^2} = I\sqrt{r^2 + x^2}.$$

Other Line Constants.—The circuit conditions above discussed are the ones most frequently used in practice. So also are the values of inductance and capacity there derived the most important. There are conditions, however, where *mutual inductance of circuits*, *inductance of line to ground*, *capacity between circuits* or *capacity of line against ground* may be of prime importance.

This group of line constants for the ordinary transmission line is not normally very important in operation with the exception in one case, perhaps, of the mutual inductance and capacity between circuits. These become of serious consequence in the case of a telephone line which closely parallels a power line. They are generally otherwise avoidable, to such an extent that their effects are neglected in calculations.

The constants of the line in respect to ground, as before stated, do not affect normal operation except under special circumstances. They become of great importance when abnormal conditions occur, such as the grounding of lines, surges upon lines, lightning discharges, etc. The most important of these will be discussed later in connection with line phenomena. At present, we will simply derive the values of such constants as will be needed in these after discussions.

In the case of two aerial lines, there exists a midplane of zero potential. The lines of force and equipotential surfaces form cylinders about the conductors, but not concentric thereto. When one line is considered as opposed to ground, the ground surface becomes the plane of zero potential. The lines of force and the equipotential surfaces about the conductor resembles those just described for one of two wires.

That is, lines of force and equipotential surfaces may be represented as if there were a return conductor below the surface of the ground at a distance equal to the altitude of the conductor above the surface. This would make the earth's surface the midplane of zero potential. The convention usually refers to the subterranean conductor as the *imaginary conductor* or the *image* of the real conductor.

The calculations then proceed as before and we arrive at expressions identical with those reached previously, namely:

$$0.0805+0.741 \log \frac{d}{r}=L \text{ per mile of conductor,}$$

$$\frac{0.03878}{\log \frac{d}{r}}=C \text{ per mile of conductor,}$$

where the symbols are interpreted according to the above discussion, giving

L = inductance against ground, in millihenrys,

C = capacity against ground, in microfarads,

d = $2h$ = twice the height of conductor above ground (i.e., the interaxial distance between the real conductor and its image).

r = radius of conductor.

logs are taken to base 10.

This restatement of symbols introduces nothing new except the broadening in order to include the imaginary return conductor.

We may, therefore, consider the two cases as identical, and make use of the same fundamental conceptions.

Mutual inductance, the effect of a power line upon an adjacent telephone line furnishing a noteworthy example, is a measure of the flux set up by the one line and interlinked with the other circuit, for proper units of current, etc.

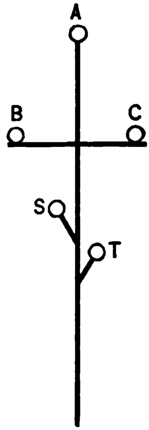


FIG. 197.—Induced potential in telephone line.

In order to calculate this effect, it is, therefore, necessary to derive, first, a statement for flux interlinkages. Fig. 197 shows a power circuit A, B, C, with a telephone circuit S, T upon the same pole line. It is evident that the flux interlinked therewith depends upon the distance from one circuit to the other, the position of the telephone wires in respect to each other and the power line and the distance between the telephone conductors.

Let

a_s = distance between A and S.
a_t = distance between A and T.
b_s = distance between B and S.
b_t = distance between B and T.
c_s = distance between C and S.
c_t = distance between C and T.

The effect between A and S and between A and T will be, respectively,

$$L_{as} = 0.0805 + 0.741 \log \frac{a_s}{r} \text{ millihenrys per mi. of conductor.}$$

$$L_{at} = 0.0805 + 0.741 \log \frac{a_t}{r} \text{ millihenrys per mi. of conductors.}$$

The difference between these two values (M_a) gives a measure of the local disturbance of the circuit ST by the wire A. This is

$$M_a = L_{as} - L_{at} = 0.741\left(\log \frac{a_s}{r} - \log \frac{a_t}{r}\right) = 0.741 \log \frac{a_s}{a_t}.$$

Similarly,

$$M_b=0.741\left(\log\frac{b_s}{r}-\log\frac{b_t}{r}\right)=0.741\log\frac{b_s}{b_t}.$$

$$M_c=0.741\left(\log\frac{c_s}{r}-\log\frac{c_t}{r}\right)=0.741\log\frac{c_s}{c_t}.$$

These three inductances are components of the *mutual inductance* of the two circuits, but they are displaced from each other in time phase by 120°. They add vertorially, therefore, giving, by means of resolving them into components along M_a and perpendicular to M_a,

$$\begin{aligned}M&=\sqrt{[(M_a-M_b\cos 60°-M_c\cos 60°)^2+(M_b\sin 60°-M_c\sin 60°)^2]}\\&=\sqrt{\{[M_a-\tfrac{1}{2}(M_b+M_c)]^2+\tfrac{3}{4}[M_b-M_c]^2\}}\\&=\sqrt{[M_a^2+M_b^2+M_c^2-M_aM_b-M_aM_c-M_bM_c]}\end{aligned}$$

where M is the mutual inductance between the two circuits measured in whatever units, L_a, L_b, and L_c are, generally millihenrys. The induced voltage in the circuit ST will be,

$$E=Ix=2\pi fMI,$$

where,

f = frequency in cycles per second,
M = mutual inductance in henrys,
I = current in amperes,
E = voltage.

Electrostatic induction between the two circuits induces a charge upon the telephone circuit. This places the telephone conductors at a potential against ground. The potential may be high enough to introduce considerable danger into the ordinary process of merely handling the telephone receiver.

The potential of the wire S, Fig. 197, will be calculated by the same process that was used in determining the potential of one wire in the problem of line capacity. The limits of integration will be determined by the distance of S from the neutral plane, the earth's surface.

For the sake of convenience, let the distance of each conductor from ground be represented by the minor of the same letter as is used for the wire (a, b, c, s, t).

Then, approximately, we have the following results,

$$\text{Potential to } A = \int_r^a \left(\frac{2Q}{x}+\frac{2Q}{2a-x}\right)dx = 2Q\log_e\frac{2a-r}{r}$$

$$\text{Potential to } S = \int_{a-s}^a \left(\frac{2Q}{x}+\frac{2Q}{2a-x}\right)dx = 2Q\log_e\frac{a+s}{a-s}$$

If it is desired to state the latter in terms of distance between main and telephone line, A to S, the form becomes, if $a_s = a - s$,

$$\text{Potential to } S = 2Q\ log_e\frac{2a-a_s}{a_s}.$$

The form of this expression is, of course, similar to that for potential of A, where r is replaced by a_s.

These potentials are expressed in absolute units and in terms of natural logarithms, but they have the same ratio as the voltages of the two wires and, moreover, the logarithms may be taken to base 10, as we are interested only in their relative values in this particular case.

$$\frac{e_a}{E_a} = \frac{\log\frac{a+s}{a-s}}{\log\frac{2a-r}{r}} = \frac{\log\frac{2a-a_s}{a_s}}{\log\frac{2a-r}{r}}.$$

If, then, the potential of A is E_a, the potential of S above ground due to A, will be

$$e_a = E_a\frac{\log\frac{2a-a_s}{a_s}}{\log\frac{2a-r}{r}}.$$

Similarly, if

$$b-s=b_s$$
$$c-s=c_s$$

we have potentials of S due to B and C, respectively,

$$e_b = E_b\frac{\log\frac{2b-b_s}{b_s}}{\log\frac{2b-r}{r}},$$

$$e_c = E_c \frac{\log \frac{2c - c_s}{c_s}}{\log \frac{2c - r}{r}}.$$

The potential of S will be the vector sum of these three quantities taken at angles of 120°.

$$E_s = \sqrt{[e_a - \tfrac{1}{2}(e_b + e_c)]^2 + \tfrac{3}{4}[e_b - e_c]^2}$$
$$= \sqrt{e_a^2 + e_b^2 + e_c^2 - e_a e_b - e_a e_c - e_b e_c}.$$

The potential of T above ground will be different from that of S, inasmuch as the distance t is not equal to the distance s, but it would be derived in the same manner.

Line Regulation.—Having determined L and C, and thence x_l and x_c, the value of the line drop is

$$E_z = I\sqrt{r^2 + (x_l - x_c)^2} = I\sqrt{r^2 + x^2}.*$$

The vector of voltage required to overcome this line drop must be subtracted from the vector of generator voltage in order to ascertain the vector of delivered or receiver voltage. Or, vice

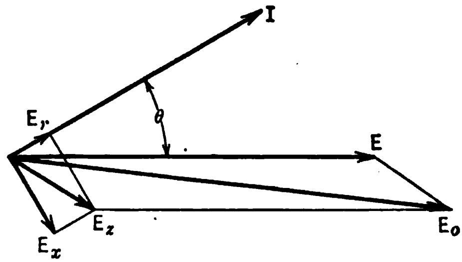


Fig. 198.—Line regulation.

versa, it must be added to the receiver voltage in order to obtain the generator voltage.

This is the problem of calculation of *line regulation*. It may be solved graphically, trigonometrically or by complex quantities. Probably the second method is as satisfactory as any for the actual calculations, being more accurate than the graphic

* We here assume that capacity and inductance of the line are in series with each other. In point of fact, in a transmission line they are distributed as will be mentioned again soon and in the calculations of a subsequent chapter this is recognized.

method in cases of small line currents. A familiarity with all three methods, however, permits their efficient commingling, as will be done here.

Figure 198 will make the problem clear.

Let

E_o = generator voltage,
E = receiver voltage,
I = current,
r = resistance of line,
$x = x_l - x_c$ = reactance of line,
z = impedance of line,
$\cos\theta$ = power factor.

It is generally advantageous in power utilization if E, the receiver voltage, can be kept constant, allowing the generator to regulate for varying line drop. This variation in line drop may be caused by change of load or change of P. F. of the load.

Suppose, then, that E is constant. We may use it as the initial line. At an angle θ with E will be laid off I, lagging if the load is inductive, leading if the load is condensive. In this case, we will assume a lagging current in respect to the voltage. The vector for voltage required to overcome impedance drop is easily located by combining $E_r = Ir$, in phase with the current, with $E_x = Ix$, 90° ahead of E_r. This gives E_z, which adds to E in order to obtain E_o, the voltage required at the generator. The vector diagram shows relations of the quantities in both magnitude and phase. It is, therefore, evident that to E must be added the projections of E_r and E_x upon the initial line, while their projections upon a line perpendicular to the initial line will be added at right angles. Hence,

$$E_o = \sqrt{(E + Ir\cos\theta + Ix\sin\theta)^2 + (Ir\sin\theta - Ix\cos\theta)^2}.$$

With leading current, the expression is identical with the above, but the $\sin\theta$ becomes negative and thus affects the results.

If E_o is constant, this expression may be used in the form,

$$E = \sqrt{E_o^2 - (Ir\sin\theta - Ix\cos\theta)^2} - (Ir\cos\theta + Ix\sin\theta).$$

These equations are identical with those in complex quantities

if we remember the conventions that in this case may be stated as

$$I\cos\theta = i.$$
$$I\sin\theta = i'.$$
$$E = e, \text{ being initial line.}$$
$$\dot{E}_o = e_o + je'_o$$

Therefore,

$$\dot{E}_o = e_o + je'_o = (e + ir + i'x) + j(i'r - ix),$$

where the symbol j indicates the right angle relation between the vectors to be combined. Or, again,

$$\begin{aligned} e &= e_o + je'_o - j(i'r - ix) - (ir + i'x) \\ &= e_o - ir - i'x + j(e'_o - i'r + ix). \end{aligned}$$

This process of finding the line drop and, thence, the required generator voltage, properly applies to a single-phase circuit. With a three-phase circuit it should be calculated in respect to neutral, as for each leg we would duplicate this calculation quantitatively. Voltage between lines is then ascertained by multiplying leg voltage by $\sqrt{3}$.

Charging current of the line is

$$\dot{i}_c = \frac{E}{x_c} = \frac{E}{1/2\pi fC} = 2\pi fCE.$$

where

E = voltage to neutral,
i_c = charging current at generator,
C = capacity to neutral measured in farads,
f = frequency.

This current does not traverse the whole length of the line, as the total capacity is not concentrated at the end of the line but is distributed approximately uniformly along the entire length. It is, obviously, incorrect, therefore, to calculate line drop for this current for the whole length of line or to assume the charging current as combining with load current at the receiver end. The accurate calculation for these conditions becomes complicated, so that approximations are made. The effect of this variation in charging current along the line is to vary not only

the quantity of current, but also the current phase, because, to a given load current is added a right-angle component of changing length. This phenomenon is noticed, especially, in connection with long-distance transmission lines, underground cable systems, high-potential transformer windings and reactance coils for high-frequency currents.

There are several methods of solution possible which more or less closely give satisfactory results depending upon conditions.

When charging current is less than 25 per cent. of load current, with about 10 per cent. line losses, it is generally sufficiently accurate to assume the capacity as concentrated in one condenser shunted across the line at the middle point. Above these values, up to perhaps a 50 per cent. charging current, or for more refined calculations with the lower values, an increased reliability will be attained by assuming the capacity as made up of three parts, one-sixth at each end and two-thirds at the center of the line.

As an example of inaccurate results reached in some cases, Steinmetz shows the necessity for refined calculations for one particular case in his book "Transient Electric Phenomena and Oscillations." In this case the line-to-neutral voltage was 60,000 volts, the load delivered 200 amperes at 90 per cent. power factor lagging current, frequency 60 cycles, length of line 200 miles. Roughly, the charging current was 65 per cent. and the line drop about 15 per cent. Calculated accurately, the results may be tabulated as in the first three columns of Table XXIV.

Table XXIV.

Capacity.	Distributed.			None.	Rec.	Gen.
Condition at	Rec.	Mid.	Gen.	Gen.	Gen.	Gen.
Current.	200	178	175	200	186	176
Voltage.	60000	66400	70700	76400	66000	76400
Power factor.	0.90	0.979	0.993	0.83	1.00	0.93
	lag.	lag.	lead.	lag.		lead

By entirely neglecting the line capacity the fourth column of the same table is obtained. The fifth column gives results when the entire capacity is supposed to be concentrated at the receiver end of the line and the sixth column represents conditions with total capacity located across the line at the generator. The actual current in the line varies from less than 175 amperes near the generator to 200 at the receiver, while the approximations of the last three columns made to represent conditions at the generator vary from 176 amperes to 200 amperes. The lower value *happens* to be very close to the actual value. None of the approximations is at all satisfactory for voltage conditions, while, for power factor, the fifth column is very close.

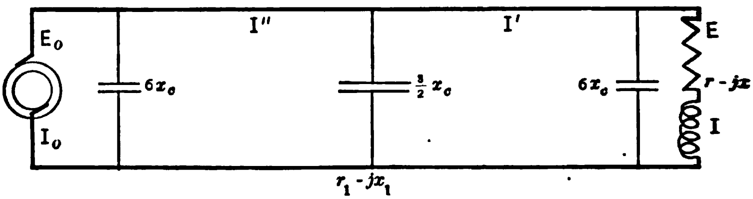


FIG. 199.—Line calculation.

One noteworthy point already mentioned is the variation in the power factor from point to point along the line. Beginning at the generator where there is a power factor of 0.993 with a leading current, the decrease in charging current along the line first increases the power factor to unity as total current comes into phase with electromotive force, then, with continued decrease of charging current, the effect of inductance becomes more and more noticeable, as it is not balanced by the lessening capacity. The total current becomes lagging and increases in amount till it reaches 200 amperes at the receiver. Meanwhile, the power factor has decreased from unity to 0.90. The minimum current upon the line will occur at the point where the power factor is unity and will be close to the generator end of the line. It will amount to less than 175 amperes.

When nearer approximations than the above are necessary, yet without requiring an absolute solution, it is possible to solve the problem by use of complex quantities. For example, assuming the total capacity divided so that one-sixth is at each end of the

line and two-thirds is at the center, the current values are four in number, the voltages three in number, etc., thus, Fig. 199.

Let $r_1 - jx_1$ = total impedance of line not including capacity.
x_c = capacity reactance of line.
$r - jx$ = impedance of load.
$\dot{E}, \dot{I}$ = e. m. f. and current for load.
$\dot{E}_o, \dot{I}_o$ = e. m. f. and current of generator.
$\dot{E}'$ = e. m. f. across line at the center.
$\dot{I}'$ = current in half line nearer load.
$\dot{I}''$ = current in half of line nearer generator.

Of these quantities, receiver voltage and impedance and line impedance and capacity reactance are supposed to be known, or they may be calculated from known data. That is, $\dot{E}$, $r - jx$, $r_1 - jx_1$, and x_c are known. The three separate condensers have reactances inversely proportional to their capacities,

$$6x_c,\ 6x_c \text{ and } \tfrac{3}{2}x_c.$$

Calculations must be made step by step from the receiver end of the line, for current, line drop, voltage, etc.

$$\dot{I} = \frac{\dot{E}}{r - jx}.$$

$$\dot{I}' = \dot{I} + \frac{\dot{E}}{j6x_c}$$

$$\dot{E}' = \dot{E} + \dot{I}'\frac{r_1 - jx_1}{2}$$

$$\dot{I}'' = \dot{I}' + \frac{\dot{E}'}{j\,\frac{3}{2}x_c}$$

$$\dot{E}_o = \dot{E}' + \dot{I}''\frac{r_1 - jx_1}{2}$$

$$\dot{I}_o = \dot{I}'' + \frac{\dot{E}_o}{j6x_c}.$$

The power factor at any of the above points upon the line is determined by the phase relation of current to voltage at that

point. This is determined by calculating the amplitude of each one from the initial line, then taking the difference between these two angles. The cosine of the difference gives the power factor.

E may be taken as the initial line and is then equal to e, having no j component.

Or finally, a most satisfactory approximation may be attained by using the first few terms in an exponential infinite series which expresses the true relation.. Steinmetz shows in his book "Engineering Mathematics," p. 204 *et seq.*, that only a few terms of the series are ever required for practical determinations and generally the calculation is much simplified.

Let

$\underset{\cdot}{E}$ and $\underset{\cdot}{I}$ obtain for conditions at receiver end of line,

$\underset{\cdot}{E}_o$ and $\underset{\cdot}{I}_o$ obtain for conditions at generator end of line,

$\underset{\cdot}{Z}_1 = r_1 - jx_l$ obtain for total line,

$Y = \dfrac{1}{jx_c}$ obtain for total line.

In no case need we go beyond the equations:

$$\underset{\cdot}{E}_o = \underset{\cdot}{E}\left(1+\frac{Z_1Y}{2}+\frac{Z_1^2Y^2}{24}+\dots\right)+Z_1\underset{\cdot}{I}\left(1+\frac{Z_1Y}{6}+\frac{Z_1^2Y^2}{120}+\dots\right)$$

$$\underset{\cdot}{I}_o = \underset{\cdot}{I}\left(1+\frac{Z_1Y}{2}+\frac{Z_1^2Y^2}{24}+\dots\right)+Y\underset{\cdot}{E}\left(1+\frac{Z_1Y}{6}+\frac{Z_1^2Y^2}{120}+\dots\right)$$

In these equations, the quadratic terms of the second member may generally be neglected without much error. Moreover, the second parentheses contain a fraction $\dfrac{Z_1Y}{6}$ which will be multiplied by the coefficient Z_1 or Y and hence may also be neglected. This gives

$$\underset{\cdot}{E}_o = \underset{\cdot}{E}\left(1+\frac{Z_1Y}{2}\right)+Z_1\underset{\cdot}{I}.$$

$$\underset{\cdot}{I}_o = \underset{\cdot}{I}\left(1+\frac{Z_1Y}{2}\right)+Y\underset{\cdot}{E}.$$

Natural Frequency.—When concentrated inductance and concentrated capacity are present in series on the same line, they are opposed in action. If balanced in effects, the circuit has an

impedance of only the effective resistance, giving *resonance*. This is indicated algebraically in the equation for current, thus,

$$I=\frac{\dot{E}}{r-j(x_l-x_c)}$$

or

$$I=\frac{E}{\sqrt{r^2+(x_l-x_c)^2}}.$$

Resonance occurs when $x_l=x_c$, or when

$$2\pi fL=\frac{1}{2\pi fC}.$$

With given L and C, varying frequency will give resonance when

$$f=\frac{1}{2\pi\sqrt{LC}}.$$

Under such circumstances, current in the circuit is limited only by the effective resistance and may rise to values destructive to apparatus.

Steinmetz shows in "Transient Electric Phenomena and Oscillations" that, when capacity and inductance are distributed as is the case in a transmission line, the above expression for frequency at resonance gives place to

$$f=\frac{1}{4\sqrt{LC}}.$$

This is called the *natural frequency* of the line, because it is the value at which the circuit resonates. The value of L and C are in henrys and farads.

If for L and C are substituted their values as derived by calculation for the whole line of length l miles,

$$L=l\left(0.0805+0.741\log\frac{d}{r}\right)10^{-3}\text{ henrys,}$$

$$C=l\left(\frac{0.03878}{\log\frac{d}{r}}\right)10^{-6}\text{ farads,}$$

we will have the expression, by neglecting the constant 0.0805,

$$f=\frac{47000}{l}.$$

Thus, the natural frequency of a transmission line may be obtained by knowing simply its length in miles. Ordinarily, the constant that is neglected in the above discussion is very small compared to the remaining member of the formula.

It is interesting to note that the propagation of the wave along the line is of the same velocity as that of light. Consider the line as one-quarter wave length and the wave length $4l$.

The velocity of light divided by the wave length will give the number of waves existing in the distance traversed in the one second, that is, it will give the number of cycles per second which is the natural frequency of the line.

$$f=\frac{188000}{4l}=\frac{47000}{l}.$$

CHAPTER IX.

GENERATION.

Primary among the sources of power for driving electrical generators is hydraulic power. Steam is of equal importance, being used alike for large outputs or power generation where the total output is smaller than would be seen in connection with water development. In many instances, gas engines are now worthy competitors of the older and more firmly established prime movers. Only a rigid examination of each individual case can determine the most economical method of operation. Some of these investigations are remarkably simple and definite, while others are difficult and result in ambiguity. In many localities, the question of water power does not enter into consideration, for the simple reason that the only available site for development is distant too far for economy of transmission. This occurs mainly in connection with small developments, as large plants have a much greater economical radius, frequently reaching 150 miles to 200 miles. Some such lines are now established, while others are projected of much greater extent.

It is impossible to establish definite maximum radii for given amounts of power, because the figures are greatly influenced by local conditions in regard to the cost of development and generation and the value of transmitted power. With ordinary conditions, rough values of economical radii might be taken as in the Table XXV. But it must be noted that only general dependence can be placed upon such figures for the reasons above stated and that variations of the order of 100 per cent. or more will be common.

Hydraulic Power.—When a water-power site is available, or when there is a possibility of its development, a thorough study of all data concerning it is necessary. For many localities there are government records of stream flow for a series of years, showing maxima and minima, duration of flood periods and drouth, etc. The number of square miles of area drained with

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precipitation records for an extended period of years gives a further check upon calculations. The percentage of total rainfall which drains off in a stream depends upon several things, important among which are the nature of the soil and its covering, drainage area, the intensity of the precipitation, the concentration of precipitation or melting snows within short periods of time, the condition of the soil as regards frost when the rainfall or thawing occurs, etc. It has been found that the run-off varies between the general values 15 to 60 per cent. In small basins, it is interesting to note that the discharge may *exceed* the precipitation in the total basin, due to springs. Such a case is recorded for the catchment basin of Graefenberg Creek, N. Y. In this instance the area is very small and the runoff is quite uniform.

Table XXV.—Economical Radii for Transmission of Power.

Miles.	Kw. minimum.
1	10
2	25
5	50
10	300
25	1000
50	5000
100	10,000
150	25,000
200	40,000
300	60,000

Variations in the discharge rates are large for streams in general. At Little Falls, N. Y., the Mohawk River, in 1905 gave variations from 511 second-feet (cubic feet per second) to 20,883 second-feet. The two extremes occurred during the same month, March. The mean discharge for the year was 3,253 second-feet, amounting to a volume equivalent to a body of water covering the entire tributary area, 1306 square miles, to a depth of 33.84 inches. Similar data concerning the Watauga River near Elizabethton, Tenn., for 1905, give as maximum rate for the year, 10,100 second-feet and as minimum, 205 second-feet, with a mean of 850 second-feet. The run-off was equivalent to a

depth of 28.29 inches over the drainage area of 408 square miles. A smaller stream, the Olentangy River, near Columbus, Ohio, with a drainage area of 520 square miles, showed a maximum discharge rate of 7,080 second-feet for May, 1905, while in October of the same year the rate fell to 1 second-foot. For the year the run-off probably amounted to more than 12 inches.

Reliable and extensive data generally are obtained only with difficulty if they are at all obtainable. It remains, therefore, for the engineer to secure for himself the definite knowledge upon which to base his operations. Even then, too much reliance must not be placed upon the data; for, as is shown the last few years, minima never before reached may occur with deforestation, etc. There are numerous methods for obtaining readings upon stream discharge. They may be classified under the three heads, *weir method*, *velocity method*, and *slope method.*

The measurements based upon weir method are more reliable than others, but this is applicable only to small streams. The accuracy depends upon the fact that, owing to the comparatively small discharge, the entire volume of water is carried over the crest of a specially constructed dam or weir, the discharge characteristics of which have been standardized so that measurements of depths of overflow permit direct calculation of the volume of water discharged.

The standard weir is a rectangular opening of such dimensions that the depth of water over the horizontal crest is between one-fourth and one-eighth the length of that crest. Discharge is restricted at each end of the crest by upward projections which are sharply beveled on the downstream side. The opening may be simply a notch cut into a board, or more elaborate construction may be used if greater permanence is desired. The length of crest should not be greater than two-thirds the stream width, and sufficient pondage should be secured to bring the velocity of approach down to 1 or 2 feet per second. The depth of water upon the weir is not measured at the crest, where the over-fall (of a distance equal to two or three times the water depth) has increased the velocity and lowered the depth, but is measured at a point at least 3 feet back of the crest, the actual distance depending upon the curve of the water surface. This is done by setting a stake at this point and driving it to a level with the weir crest. Depth

over the stake is then called the head over the weir. The adjustment of these dimensions for a given case requires some preliminary approximations. When the conditions are obtained, however, the volumetric measurements may be calculated from the readings by formula or by use of tables. The formula used is

$$Q=3.33(L-0.2H)H^{3/2}$$

where Q is the quantity of water discharged, measured in cubic feet per second; L is the length of the weir in feet; H is the head of water over the weir in feet. Or, by referring to Table XXVI, we will find given the number of cubic feet of water discharged per minute per inch length of weir crest, for various depths of water measured in inches. If the weir crest is of the same length as the stream width, a different formula must be used, namely, $Q=3.33\ LH^{3/2}$.

Table XXVI.—Weir Measurement.

Giving Cubic Feet of Water per Minute, that will flow over a Weir 1 inch wide and from 1/8 to 20 7/8 inches deep.

Inches.	0	1/8	1/4	3/8	1/2	5/8	3/4	7/8
0	0.00	0.01	0.05	0.09	0.14	0.19	0.26	0.32
1	0.40	0.47	0.55	0.64	0.73	0.82	0.92	1.02
2	1.13	1.23	1.35	1.46	1.58	1.70	1.82	1.95
3	2.07	2.21	2.34	2.48	2.61	2.76	2.90	3.05
4	3.20	3.35	3.50	3.66	3.81	3.97	4.14	4.30
5	4.47	4.64	4.81	4.98	5.15	5.33	5.51	5.69
6	5.87	6.06	6.25	6.44	6.62	6.82	7.01	7.21
7	7.40	7.60	7.80	8.01	8.21	8.42	8.63	8.83
8	9.05	9.26	9.47	9.69	9.91	10.13	10.35	10.57
9	10.80	11.02	11.25	11.48	11.71	11.94	12.17	12.41
10	12.64	12.88	13.12	13.36	13.60	13.85	14.09	14.34
11	14.59	14.84	15.09	15.34	15.59	15.85	16.11	16.36
12	16.62	16.88	17.15	17.41	17.67	17.94	18.21	18.47
13	18.74	19.01	19.29	19.56	19.84	20.11	20.39	20.67
14	20.95	21.23	21.51	21.80	22.08	22.37	22.65	22.94
15	23.23	23.52	23.82	24.11	24.40	24.70	25.00	25.30
16	25.60	25.90	26.20	26.50	26.80	27.11	27.42	27.72
17	28.03	28.34	28.65	28.97	29.28	29.59	29.91	30.22
18	30.54	30.86	31.18	31.50	31.82	32.15	32.47	32.80
19	33.12	33.45	33.78	34.11	34.44	34.77	35.10	35.44
20	35.77	36.11	36.45	36.78	37.12	37.46	37.80	38.15

The vertical column gives the integer; the horizontal row of headings gives the fraction of water depth in inches. For example, corresponding to a depth of water upon the weir crest of 10 3/8 in. we have a discharge per in. width of 13.36 cu. ft.

If the crest of the weir is wide, as in the case of a dam, flow is retarded. Again, if the velocity of approach is not negligible, it becomes necessary to add to the measured value of the head an equivalent *velocity head*, thus, with contractions at the ends of the weir,

$$Q=3.33(L-0.2H)\ [(H+h)^{3/2}-h^{3/2}].$$

or, without contractions,

$$Q=3.33\ L[(H+h)^{3/2}-h^{3/2}].$$

In these formulæ, the coefficient as determined in eighty-eight experiments varied from 3.30 to 3.36. Hence the average value 3.33 is used. These are known as the Francis formulæ.

The value h, *velocity head*, is

$$h=\frac{V^2}{2g}=0.0155V^2=0.0155\left(\frac{Q}{A}\right)^2$$

where $A=$ area of cross-section.

The velocity method of measurement of stream flow consists of the determination of the cross sectional area of the stream at a given point and the mean rate of flow past that point.

Of these two determinations, the cross-section may be obtained with any degree of accuracy desirable, although it will not remain constant. The great difficulty lies in the determination of the velocity of flow. This quantity depends upon the surface slope, the wetted perimeter, roughness of the bed and channel conditions. The gaging station must be located where these conditions give most uniform and representative results. A straight channel, above and below; absence of cross currents and tributary streams; high banks not subject to overflow; clean channel; absence of dams; all of these are necessary conditions for the location of the gaging station.

The process of taking the records consists in estimating the relation between height of water and its rate of flow, thus establishing a *rating curve* for the station. Subsequent daily readings are then made from the gage, showing height of water, and the discharge rate is taken from the station rating curve, Fig. 200. This curve, after once having been calculated, must be corrected from time to time or allowances made in order to compensate for shifting river beds, presence of ice, etc. As the accuracy depends

so completely upon the station rating curve, great care is taken in its preparation.

Stream velocity may be measured by floats or by meters. If a surface float is to be used, a corked bottle with a small flag is about as satisfactory as any kind. The float is timed over a measured stretch, numerous readings being taken and averaged. A coefficient must be used, then, to reduce this to mean velocity. The use of this reduction constant is avoided if there is used a

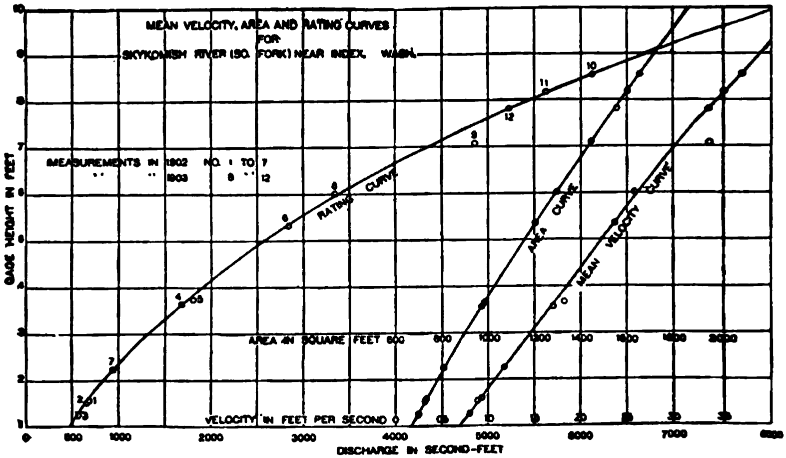

FIG. 200.—Rating, area, and mean velocity curves for South Fork Skykomish River near Index, Wash.

rod float or subsurface float. The former quite satisfactorily averages the flow as it presents body to both the slow moving water and that moving more rapidly. In straight, even channels, as canals, this is very satisfactory. The subsurface float, combinations of surface and subsurface, etc., will likewise give acceptable average readings if a sufficient number of readings are taken. These readings are taken at different points across the stream, each point being read many times. A curve may then be plotted with stream width as abscissæ and velocity readings as ordinates, Fig. 201. The average velocity will be represented by the average height of the curve.

Or, in order to avoid some of these calculations of velocities

from the time readings, we may plot time readings against distance, as in Fig. 202. The average ordinate will then represent the average time over the course, from which the average

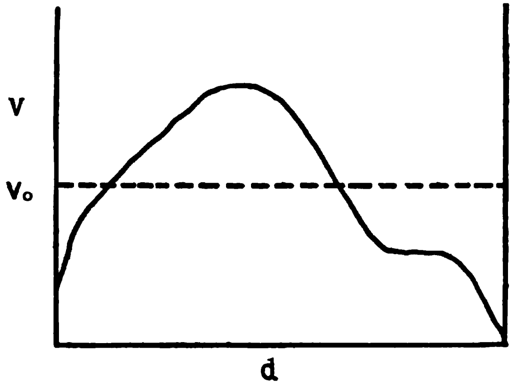

FIG. 201.—Computation of average stream velocity.

velocity is immediately derivable. The area of cross-section of stream, upon which volumetric calculations are based when float measurements are taken, must be a mean value for the course over which the velocity measurements are taken.

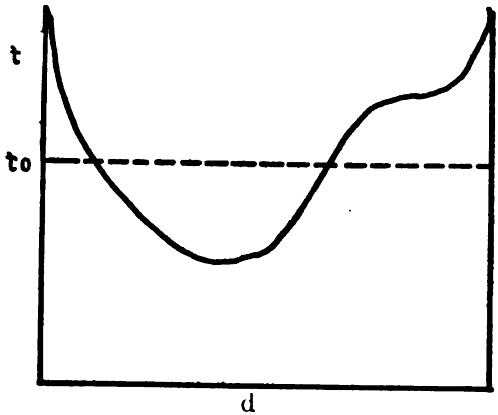

FIG. 202.—Computation of average time over course.

Current meters are of many forms, but may be classified according to the type of vane used upon the moving wheel. One form uses the screw propeller, another uses the hemispherical cup-

shaped vanes. The wheel being held in a fixed position in the stream, its number of revolutions for a given time must be recorded or counted. A calibration sheet for the meter then gives the corresponding velocity reading. These readings are taken at regular points across the stream, each section into which the stream is divided being calculated individually and the discharges added. The total discharge divided by the area of cross-section gives the mean velocity for the stream.

There are three methods of taking the meter readings. The *single point* method requires the reading at some one particular depth of stream. This may be at the mean velocity point (namely, 0.6), or at some other depth the relation of whose velocity to mean is known. For flood conditions, readings a foot below the surface may be reduced to average by the use of a coefficient of about 0.9.

The *multiple point* method make use of sets of readings taken at different specified depths, the method of calculation of the average velocity depending upon where these readings are taken. The most elaborate of these necessitates many readings taken at depths varying uniformly by 6 inches to 1 foot. This gives a vertical velocity curve to be averaged. If it is assumed that this curve is parabolic in form, such numerous readings may be replaced by two readings taken at 0.2 and 0.8 of full depth, using the mean thereof.

The third method for meter practice is the *integration* method. This process consists in moving the meter at a slow, uniform speed from the surface of the stream to its bottom, reversing the direction, and bringing it to the surface. The reading obtained is thus a double integration over the vertical depth. The presence of an ice covering very materially decreases the mean velocity and the integration method of measurement is especially successful here.

These processes are all accurate and reliable, to a degree comparable to the permanence of conditions affecting the flow. Prime among the variables in many streams is the shifting of sand and soil in the stream channel. Where this factor enters, the only safe procedure is to multiply the number of readings, taking them at very frequent intervals, and interpolate for intermediate conditions.

The effect of wind upon velocity and discharge is also considerable if the prevailing directions of winds are the same as the stream course and if heavy winds are common.

It should be noted that stream measurements taken during rising or falling gage-heights are not typical of mean-slope conditions, and no rating curves should be based upon such readings. Only inaccurate discharge rates can be estimated therefrom because they are affected to the degree of the rapidity of the rise or fall. If it is desired to estimate discharge under these conditions, it may be done roughly by calculations based upon *im-slope of the stream.* This method is also available when flood marks remain upon the stream banks after the fall of the river to normal gage height.

Available head for power development can be estimated by use of survey records or directly by a special surveying party sent to study the situation. Occasionally, natural conditions exist such that the whole development may be located within a very short distance along the river. Such might be the case when considering installations at water-falls. Even here, however, rapids above or below the falls may not be developed without more extended construction. But where slope is uniform for a great distance or does not become large for any small distance, it becomes necessary to provide artificial ways in which the available head is divided up into three parts. There is first, the head required for maintaining the supply, then the utilized head and, lastly, the head required to discharge the water from the tail race.

In some instances, as in the plants at Niagara Falls, the water may be taken directly from the river by use of deflecting piers, as the water used constitutes only a small part of the discharge. Where, however, any considerable proportion of the water volume is to be required, normally or under conditions of minimum flow, a dam is constructed to control the flow. It will serve the double purpose of control of flow and the increase of head. It is very commonly used to give concentration of head with no further diversion of water into courses having more gradual slope than the stream itself. This latter is practicable, however, and an increase in head may be derived therefrom, if the river slope below the dam is greater than that which is necessary for the

supply head. The question arises, then, as to whether this possible increase in head is worth, in dollars and cents, the cost of its development. In the case of rapids, this will nearly always be a paying investment, unless the total fall is very large compared to the available increase and water supply is unlimited.

The head utilized by the water motor may be or may not be concentrated at a point and each arrangement is often met with. The water, after having been deflected into the channel to the motor, may be led to the latter through an open water way. In such case, as little head should be used in the canal as is consistent with continued and reliable water supply as none of the head here utilized counts for development of power at the turbine. This canal will lead to a pond as near to the power-house site as is possible. From the pond, direct closed pipe-lines running full lead to the motors, making use of the head from water level of the pond to water level in tail race. While vertical pipes are not always obtainable, these closed pipe-lines are as steep as is possible in order to avoid friction losses due to long conduits.

Where the topography will not permit of this arrangement, a long pipe line may be established running from the point of deflection of water from the river to the site of the power-house. This line will generally be of varying steepness of grade and may even rise in short stretches. As long as it is running full, however, the total head is available as *gross head.* From this must be deducted certain amounts due to the friction losses. When a rise occurs in the pipe, at the highest point where the descent again begins, there should be placed a relief valve to provide an outlet for air which will gather at such points, being entrained by the water.

The construction of the open canal is accomplished with earthen banks, with concrete walls or lining or with wooden flumes. The cross-section depends upon the material used, both as regards the proportions and actual dimensions. That is, the concrete canal or wooden flume may be much smaller than the earthen canal for the same discharge, as the permissible water velocities differ considerably. For the former, the velocity may be 6 to 8 feet per second. For earthen canals this must be reduced to 0.5 to 2 feet depending upon the nature of the soil. The kind of soil also determines the slope of the banks.

Concrete construction is quite expensive compared to either of the other methods. It has the advantage of permanence, however. Because of the expense attached to its installation, great care should be used in its design as applied to the particular case being studied. While not of excessive size, it should be designed having an eye to future requirements. The rectangular cross-section should give place to the trapezoid with side slopes. The comparative dimensions will be adjusted according to whether maximum discharge is to be attained with minimum cross-section (i.e., cost of excavation), or minimum wetted perimeter (i.e., cost of lining). The wooden flume, however, is generally built rectangular in cross-section in order to attain simplicity of construction.

All flumes and canals should be protected as far as possible from danger of destruction by snow slides, land slides, etc., or from danger of filling due to the same causes. In some cases it is found necessary to establish a regular means of clearing the water of leaves, twigs, and debris of this nature.

No simple method is possible for calculating the flow of water in canals. The method most frequently used is expressed in a formula for velocity as follows:

$$v = c\sqrt{rs}$$

where v is the velocity in feet per second,

s is the slope,

c is a constant for a certain condition of canal wall,

r is the hydraulic radius.

The hydraulic radius r, is the quotient obtained by dividing the cross-sectional area by the wetted perimeter. To obtain the constant c in the above (Chezy) formula, Kutter has proposed the use of the expression

$$C = \frac{\frac{1.811}{n} + 41.65 + \frac{0.00281}{s}}{1 + \frac{n}{\sqrt{r}}\left(41.65 + \frac{0.00281}{s}\right)}$$

where r and s are interpreted as before and n is an arbitrary constant depending upon the roughness of the surface of the

channel. It varies between rather wide limits, but may be assumed according to the following statement of conditions.

n = 0.010 for new, well-planed, well-matched timber; new iron pipes.
= 0.011 for neat cement.
= 0.012 for smooth concrete; old iron pipes; open wooden flumes.
= 0.013 for ashlar masonry and good brickwork.
= 0.015 for rough concrete; unclean surfaces; open concrete flume.
= 0.017 for good rubble masonry; rock cuts.
= 0.020 for rough rubble masonry; rough rock cuts; poor wooden flumes.
= 0.025 for clay canals; open rivers.
= 0.030 for canals and rivers with stones and weeds.
= 0.035 for canals and rivers in poor condition.

Besides this loss of head due to friction there is frequently serious loss in volume of water from leakage of the flume. This is of considerable importance, especially with high heads, because every cubic foot of water lost per minute represents a loss of so much power. Based upon an efficiency of water wheel of 85 per cent. with a head of 100 feet, 1 cubic foot of water per minute represents about 1/6 horse-power; at 650-foot head, about 1 horse-power; at 1250-foot head, about 2 horse-power; at 1900-foot head, over 3 horse-power. Where water supply is limited or flumes are of small capacity, leakage will be a matter of considerable concern.

In closed pipes or penstocks, the losses in effective head are due to several causes. The most serious of these is friction loss. Losses due to change of size of pipe, to curvature, etc., are generally, to a large extent, reducible to minor values. It is most convenient to express the losses in terms of loss of head. The laws actually governing the friction loss are not well understood, although certain characteristic phenomena are recognizable.

The loss increases with the roughness of the surface, the length of pipe, and about as the square of the velocity of flow. It decreases with increasing diameter of pipe. We may, therefore, express the energy loss by a formula:

$$2gh_f = \frac{Clv^2}{d}$$

where h_f = "friction head,"
C = coefficient of friction with certain reduction constants,

l = length of pipe line in feet,
v = velocity of water flow in feet per second,
d = diameter of pipe in feet.

Whence, $h_f = \frac{61}{d} \cdot \frac{v^2}{2g}$

The coefficient C is to be chosen arbitrarily from test results. It varies from 0.01 for large pipes (6 feet diameter) with high water velocity (10 feet per second) to 0.04 for small pipes (1 inch diameter) with low water velocities (1 foot per second). A satisfactory first approximation for conditions usually obtaining in hydraulic practice is to use for its value the figure 0.020.

It is probably necessary, however, to use the Kutter coefficient with the Chezy formula, properly choosing the constant n from the data given in the discussion for channels and canals. This gives an expression for velocity of flow which is needed in the above expression for friction head, and is generally not known to start with.

For the conditions usually met with in hydraulic development, using pipes of uniform section and no curves except of long radius, Merriman states that the velocity of flow may be expressed thus:

$$v = \sqrt{\frac{2gh}{1.5 + f\frac{l}{d}}}$$

where h = total head,
f = friction coefficient as discussed above,
l = length of pipe,
d = diameter of pipe.

When $\frac{l}{d} = 3750$, the inaccuracy caused by neglecting the constant 1.5 in the above formula is only 1 per cent. (for $f = 0.02$). This would give us a simplified expression, thus:

$$v = \sqrt{\frac{2gdh}{fl}} = 8.02\sqrt{\frac{dh}{fl}}$$

Thence, $$q = \frac{\pi}{4}d^2v = 6.30\sqrt{\frac{d^5h}{fl}}$$

where q is the discharge per second. We recognize from this that turbines, having the same diameter and vent, vary in discharge (and in speed) as the square roots of their respective heads.

If it is required to determine the size of long pipe needed in order to discharge a given volume of water, the above formula will give:

$$d=0.479\left(\frac{flq^2}{h}\right)^{\frac{1}{5}}.$$

This shows that discharge varies as the five-halves power of the diameter, or discharge increases more rapidly than the area increases.

Long pipes are very commonly used in preference to open flumes in order to avoid some of the losses due to the latter, as leakage, evaporation, etc. If they are to replace the open flume only, they need not be made especially strong as against internal pressure. However, where they are used, the nice grades necessary for the flume may give place to a more varying profile and pressures will be increased thereby. As it is expected that they shall run full, except, perhaps, in cases of very light, uniform grades, they must be designed to withstand the pressures existing.

The materials used are wood, iron, either cast or wrought, steel, and concrete.

Where wood is used, such kinds must be selected as will have strength and durability. This construction is used where wood is plentiful and easily obtainable and where the iron or steel pipes are procurable only at a much greater expense or where transportation of pipe sections is impossible. Although subject to decay, in some localities its life is twenty to thirty years. As noted in the discussion of the preservation of wooden transmission poles, the presence of the combination, heat, moisture, and air, will invite rapid decay.

While a preservative treatment of the wood will probably defeat one purpose of the wooden pipe line—namely, cheapness, still a superficial treatment by brush or painting, etc., will undoubtedly have good results.

Wood is not generally used for heads of over 200 feet, although a figure as high as 350 feet sometimes occurs. Here, and above

this, iron or steel has the distinct advantage of being better able to stand the higher pressures. When steel pipe is used, it is rolled into sheets and then bent into cylinders and fastened with a double row of rivets. The successive sections are jointed together by the use of flanged joints, collar joints, or slip joints.

The slip joint is made by inserting the smaller end of a section in the larger end of the next section. It is used up to 300-foot heads.

The collar joint utilizes an outer collar and an inner sleeve. One is riveted to each length of pipe and they are then jointed with hot lead filling. It is claimed that this plan is satisfactory up to heads of 700 feet.

The flanged joint is made by placing upon the straight pipe a flanged collar. This collar is riveted to the same part of the next section, with rubber gasket filling in the joint. This is used for any commercial pressure.

The sections are made of any lengths from 6 feet up, as is best suited to the transportation problem. They are given coatings of asphaltum in order to decrease friction loss and to increase life.

Upon great heads, these lines are called upon to withstand severe pressures. It is not safe, however, to calculate these pressures by ordinary methods for static pressure of water columns. The most severe strains come upon the pipes when a wheel which has been running at open gate suddenly regulates to close the gate, as might be the case when a short circuit occurs upon the electric side of the system. In this case, the whole column of water, moving at some high rate of speed, is suddenly checked. The destruction of a pipe line may result from such a cause. On long pipe lines, it is practicable to increase the thickness of the conduit in the lower sections where the pressure is highest. Firm foundations and anchors must be provided for pipe lines, especially upon steep grades and at curves. In the latter case the construction must present sufficient solidity to change the direction of flow of the whole volume of water, without danger of displacement of the tube. It is at such points, whether they are lateral or vertical bends, that the effects of sudden closure of gate may be expected to appear.

If vertical tubes were inserted at different points along a pipe

line, the water would rise to certain heights in them, depending upon conditions of head and freedom of discharge. A line connecting the tops of these water columns is called the *hydraulic gradient.* With closed pipe line, it will be a horizontal line level with the surface of the supply water. With open discharge, it will be a sloping line connecting the point of water level at the source with the mouth of the tube at discharge. With restricted discharge, the fall at the nozzle is abrupt from some intermediate value to zero.

In laying long pipe lines, the pipe should not rise at any point above the hydraulic gradient. That is, the arrangement shown in Fig. 203 is not a good one. The hydraulic gradient for a full

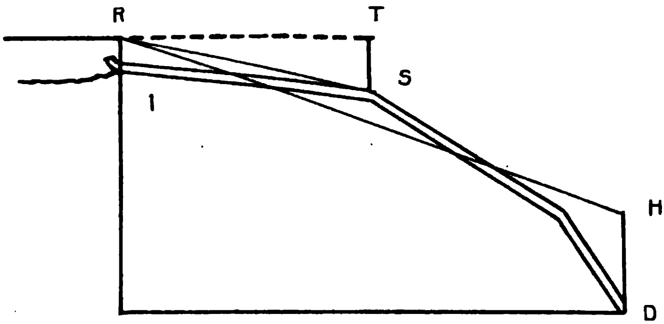

Fig. 203.—Hydraulic gradient.

pipe with restricted flow is supposed to be the line *RH* with a sudden descent at *D*, the point of discharge. The height of the line *HD* is not sufficient in this case to bring the line *RH* above the course of the pipe at *S*. This means that the portion in the region *S* is acting as a siphon. Sooner or later, the air entrained with the water will collect in the portion *S* and spoil the vacuum, upon the permanence of which the continued full flow depends. After this, the discharge will lower, being that for the head *ST*, the pipe below *S* running only partly full. In order to avoid this diminution of discharge, the air must be pumped or forced out of the bend at *S* through a discharge valve Naturally, it is preferable to avoid this complication.

Turbines.—Primarily, there are two types of water wheels developed for modern power engineering. Earlier and simpler

forms have never been satisfactory for generation of power for large systems. The two fundamental types are known as impulse turbine and reaction turbine. The former is driven by the force of the water jet impinging upon the blade. The kinetic energy of the water is thus given to the wheel, the water leaving the passages at a low velocity. In this class of wheel, the passages are not ordinarily filled with water, but flow partly full only. The velocity of the water jet is that due to the effective head.

The reaction type receives the energy of the water by the pressure upon the blade and the reaction from the blade. The passages run full. The velocity of the water may be less than that due to the head, as the flow may be restricted by the wheel. It, again, may be greater than that due to the head upon the wheel itself, because of the use of a draft tube below the turbine passages. The draft tube cannot be used with the impulse type.

When water is not admitted around the whole periphery of the wheel, the motor is generally spoken of as a water wheel in contradistinction to the turbine. In the case of the impulse wheel this reduction of the number of guide passages, through which the water is directed upon the moving blades at the best angle, may be carried to the limiting condition of one passage. In such a case, the opening becomes a nozzle and the type thus consists of a running wheel with one water jet playing upon it. This type has been developed under the name of the Pelton wheel. Frequently, the original single nozzle of the Pelton wheel gives place to muiltiple nozzles, the type, however, remaining the same.

The Pelton type is used for high heads, although it may be installed on low heads as well, if multiple nozzles are used. The Pike's Peak Hydroelectric Company uses this type for a head of 2150 feet. The Brittannia Copper Syndicate of British Columbia uses it under a head of 1900 feet. The Saõ Paulo Electric Company, Brazil, develops 1000 horse-power under a 75-foot head. The Folsom Electric Power Company, Cal. uses a 55-foot head, giving 4000 horse-power. These are typical installations, with all intermediate values of head possible.

Reaction turbines may be divided into three general types as regards their construction. These are ordinarily known as the *radial flow*, the *axial flow* and the *mixed flow*. These names indicate that the arrangements made for the water flow in the

wheel itself are such that it passes through the wheel radially (inwardly or outwardly); or, secondly, in a direction parallel to the axis; or, lastly, by a combination of these two, consisting of an inward radial entrance changing to an axial exit. These types are quite generally known by the names of their respective developers. That is, the outward radial flow is known as the Fourneyron; the inward radial flow as the Francis; the axial flow as the Jonval. The mixed-flow type, however, is called the

FIG. 204.—New American runner.

American type, as it has been chiefly developed in this country and is the one most commonly seen here. The Francis type has made rapid advance the last few years.

While there are many builders of turbines, their products differ in details principally. It is needless to multiply the examples quoted and a few only are selected in order to indicate typical development.

Figure 204 shows a runner of the American turbine type. In fact, it is called the "New American" by its manufacturers.

The compound curvature of the blades is readily seen to give the direction of water-flow above described for this type. The casing for the runner is shown in Fig. 205. The gates shown are of the *wicket type*, swinging upon pivots to close or open the water passages leading directly to the turbine vanes. These gates may

FIG. 205.—New American turbine casing.

be of different designs, as the *cylinder gate* or *register gate*. The former is a cylinder so placed that it may be lowered or raised, thus decreasing or increasing the height of the entrance passages. The register gate consists of longitudinal sections of a cylinder, which may be revolved in such a way as to narrow the passages. For variable flow, where considerable difference of power is desired or where variations are of frequent occurrence, and part

gateage is common, the wicket type of gate is given the preference, as there is no shock when the water leaves the gate passages and enters the wheel passages. With each of the other types there is a sudden increase of area just beyond the gate, with consequent eddies and whirls.

Attached to the lower part of the casing is the discharge tube, which may be extended into a draft tube if the turbine is to be set much above the tail race water level. This discharge tube or draft tube must end below water. Thus, in the installation of the wheel, low water level must be considered.

The setting shown is a vertical shaft. However, this type of wheel may be installed with horizontal shaft as readily as with vertical shaft. The choice between the two would seem to involve the arrangement made for the transmission of its power to the machinery constituting its load. This, of course, is a reciprocal relation. If the nature of the load is such that power must be or preferably should be applied through a horizontal shaft, it may be taken for granted that a considerable loss in efficiency will occur when vertical turbines are installed and bevel gears are interposed between turbine and load. Again, if the turbine is necessarily installed at the bottom of a pit or shaft, as in the Niagara plant, direct connection with the generator can be secured best by vertical shaft. Again, with very low head it is best to use the vertical shaft. The lowest head of which the author is aware is that reported for an Italian plant at Bologna where good results are secured with only a 26-inch head. The installation is of Trump turbines and it was necessary to set the wheels below the water level in the tail race.

For low heads, horizontal wheels are generally set in open flumes built of timber or masonry. They are also placed over draft tubes in order to lose no possible advantage. This open construction is less expensive in such cases and makes certain the unrestricted water flow for the supply of the turbine.

Where one turbine does not give sufficient power for the shaft, two or more turbines may be assembled upon the same shaft or else supplying power to the shaft by gears, etc. These may be upon a vertical or a horizontal shaft. This device may be resorted to in order to increase the speed of the shaft, for, if one large wheel gives place to two or three smaller ones, the water

velocity remaining the same, the peripheral velocity of the wheels will remain the same; but the decreased diameter means an increased number of revolutions per minute.

Wherever this arrangement is used, especial attention must be paid to the size of casing and to the direction of water flow therein. Not only should the piping be large (open flumes or penstocks are to be preferred), but the penstock should enter the machine casing at such a point, or at such points, that the water flow may be as nearly as possible direct to the turbine gates around their whole periphery. It is a poor arrangement to have several turbines thus upon a single shaft and have the penstock enter at one end of the casing, unless the case is very generously proportioned. Any loss in pressure will be equivalent to a loss of effective head, as is friction loss at any point of the water flow. Another arrangement which may cause loss, unless the turbine case is large, is where the water enters the case at the center point, flows to each end of it, enters the gates of two turbines (one at each end) and discharges through a single central draft tube. A more direct arrangement would be to have two end discharge tubes, the turbine gates being near the entrance point of water into the casing.

The Francis type is less frequently seen in this country than is the American type, although it has come to the front very rapidly during the past four or five years. It is being installed under what formerly would have been considered as enormous heads for the reaction type of machine. As examples, the Great Western Power Company is using them with a head of 430 feet, and the Allis-Chalmers Company is furnishing 20,500 horsepower turbines for use under 480-foot head for the White River Development.

One form in which this type appears is shown in Fig. 206. This represents the plan of a Francis-Pelton wheel, installed with vertical shaft. One-quarter of the machine is seen in section, indicating by the two rows of heavy vanes and blades both the runner blades and the guide vanes of the wicket gates. The remainder of the plan indicates, among other things, that the gates are controlled by short arms attached to an outer ring, the position of which may be shifted, thus rotating the gate wickets about their pivots.

Turbines of the above classes should show maximum efficiency in the neighborhood of 3/4 to 7/8 of their full load water flow. The percentage of full water flow is called the gate opening, this being a measure of the ratio of quantity of water allowed to enter to total flow, rather than the relative distance the mechanical parts have moved from closure. The

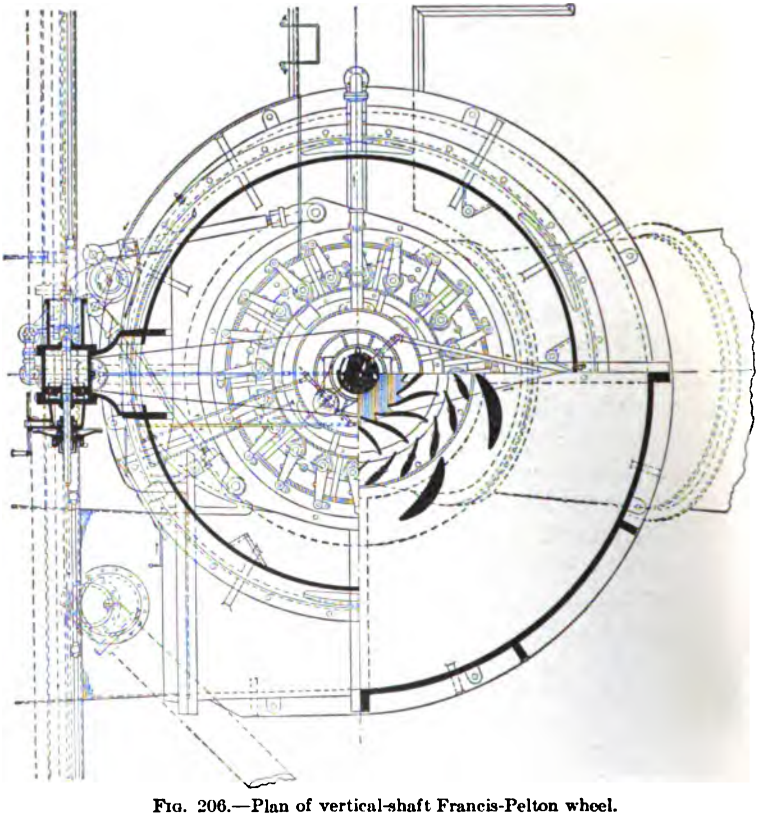

FIG. 206.—Plan of vertical-shaft Francis-Pelton wheel.

efficiencies reached may be a little above 80 per cent., as shown by the curves of Fig. 207. These curves indicate that efficiencies for some machines are fairly uniform over a considerable range of load, which is a valuable characteristic for a prime mover but does not obtain for all types of water wheels. High-efficiency wheels should be installed even at increased cost. Water power is

becoming more valuable every year and economy of its development and utilization is important.

The Pelton wheel is illustrated in Fig. 208. This particular

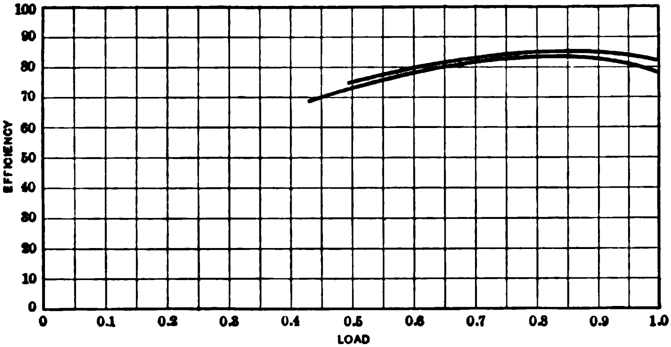

Fig 207.—Turbine efficiency curves.

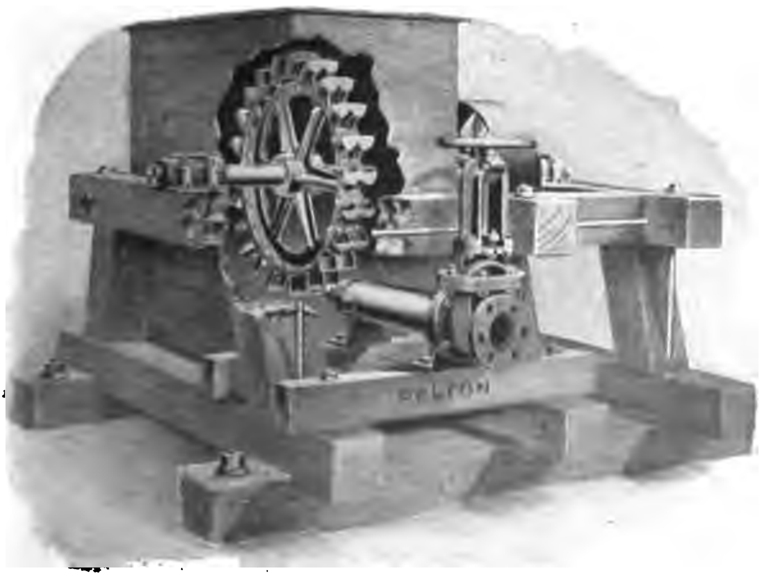

Fig. 208.—Pelton wheel for low head.

wheel is intended for use with rather low head and is installed in a wooden frame or setting. It has only one nozzle, and hence its output is rather limited. With increased volume of water,

additional nozzles may be used, but even then the amount of water discharged is necessarily less than may easily be handled with the reaction turbines. Hence, when large amounts of power are to be developed under low water head, the turbine is to be preferred. This feature, which is a disadvantage for low heads, is a decided advantage for high heads; because in this case the magnitude of the power is attained with small water discharge. With extremely high heads the small volume of water used would not fill the passages of a reaction turbine and the impulse type must be adopted. Peripheral speed will be less for the latter than for the former with the same head.

In setting turbines and wheels of all types, wooden construction may be used for low heads and small amounts of power. As the magnitude of the development increases this should give place to more substantial construction, becoming the best obtainable concrete or masonry.

As before pointed out, the head race, flume, or penstock must be of ample capacity. Where the delivery is through pipes the intake end must be well submerged and in all cases trash racks must be provided to screen out floating debris. Lack of proper attention to this latter detail may prove very expensive.

The wheel pit must be wide and deep in order to avoid loss of head in forcing the water out into the tail race. Turbulent action here indicates restricted area of section. The same is true of the tail race; it must be capable of carrying off the discharged water with the least possible effective head, because the excess head used here is simply taken from the available total head and represents a waste of power.

Turbines may be assembled in pairs, the individuals being opposed to their mates upon the same shaft. This has the advantage of balancing end thrust. Without it, a thrust bearing is necessary. With low heads the end thrust causes no great amount of trouble, but with high heads it may prove serious. Several types of settings are illustrated in Fig. 209.

The arrangement should be chosen upon the advice of the turbine manufacturer. In fact, he should be consulted early in the process of determining the layout. He desires to know the amount of water to be used, head, length of pipe line, its diameter, character of the machinery constituting the load, etc. He will

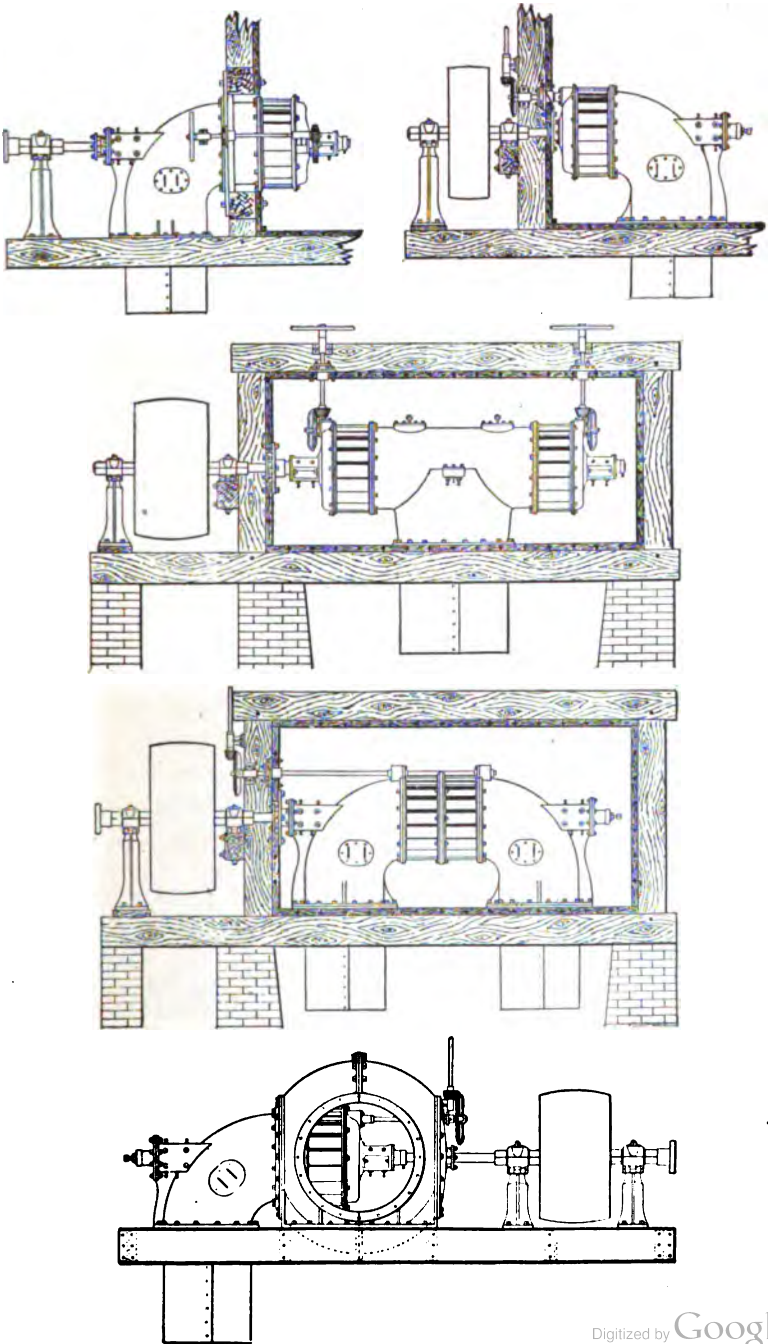

FIG. 209.—Typical turbine settings.

then be able to tell what are the principal requisites for economical development, as speed, general arrangement, etc.

Dams.—In power development, dams built to give or increase head and permitting overflow must be sharply distinguished from those built for storage of water and either permitting no overflow or having special provision for this. Where overflow is permitted, the dam must have certain quite different qualities from those required in storage only. The material must be incapable of rapid erosion. The construction must be such that the falling water cannot undermine it from the downstream side. Furthermore, the location sought for such a dam would be one where height of crest could be attained without great length, or without great impounding capacity. Of equal importance to the engineers is the possibility of sometimes placing long, low, easily constructed dams in such locations that they will back up the water to cover a large area to a nominal depth, thus impounding an immense reserve supply for seasons of low water.

In the former type of development the lines of construction vary greatly depending upon head of water, nature of river bed, availability of materials, etc. A simple form often used for low heads is the timber dam. It may be built of logs or of sawed timber and is seen with a great many variations. The chief claims made for it are ease of construction and cheapness. The latter point is becoming of less weight, owing to the increase in value of lumber. It may be combined with loose stones into *cribwork*, or large enclosures to retain the stones in place. This is effective for higher heads than that for which the plain timber dam may be used. But for high heads the use of stone masonry or concrete is required. This permits the most substantial construction, with opportunities for firmly establishing the structure. The curved surface of the dam directs the water discharge forward from its base instead of allowing it to excavate a pit at that point. Foundations of bed rock should be reached wherever possible and the dam should be firmly anchored thereto in order to avoid failure by sliding. In case of highest heads accumulated by dams, it is preferable to arrange for the necessary overflow at some particular point upon the crest rather than across the full width of stream.

Reservoir dams are quite frequently made of earth. Generally

speaking they are low and long. They are supplemented by similar structures in each of the depressions around the valley where the height of water will exceed the elevation of the land. They are liable to rapid destruction when once the process of disintegration due to overflow begins. The importance of this type of installation may be shown by a brief calculation.

A certain stream varies in discharge throughout the year from a minimum of 660 second-feet to a maximum of 3850 second-feet, averaging about 1040 second-feet. With an effective head of 10 feet and with water wheels of 80 per cent. efficiency, the low water stage will develop about 600 horse-power. The average value would permit about 900 horse-power to be utilized. By studying the stream flow it is found that, to store the excess volume of water above that required for average flow, a capacity will be needed equal to a reservoir of one-quarter of a square mile covered to a depth of 6.8 feet. But, to further analyze the conditions, it is found that an average flow from month to month may be maintained at a figure to give about 800 horse-power if the storage reservoir is one-eighth of a square mile in area and is covered to a depth of 4 feet. Thus, it might be a very questionable proceeding to plan upon the development of the maximum uniform output of 900 horse-power because the increased expense over that required for the continuous output of 800 horse-power might be too great to pay for the additional 100 horse-power.

The broad problem of the development of a water-power site, the location of the dam, the flumes, the penstocks, the power-house, the tail race, etc., must be solved with due consideration to all details. The course of the river itself may make the matter easy or difficult. If it is straight over the whole course the canals and penstocks must be of the same total length as that portion of the river developed. When curves occur, short cuts may be available and with loops the canals and pipes may be comparatively short.

An excellent example of the latter case is shown in the map of the system at Schaghticoke, N. Y., upon the Hoosick River, Fig. 210. Within a length of 2 miles, the river falls about 150 feet. There are two back loops or a letter *S*, as seen in the map. The power had been utilized in small installations for individual mills; but it was estimated that a redevelopment of the whole

amount as one system would give greater economy. Hence, a large dam was swung across the stream, a canal was dug leading to a reservoir or pond, and individual penstocks were installed for the turbines. As several points are treated in special ways, a few words may be said of the individual characteristics of the plant.

The dam raises the water level enough to flood low lands above it. At the lower end of the dam (which reaches diagonally across the river) are the sluice-ways and the canal intake. The canal

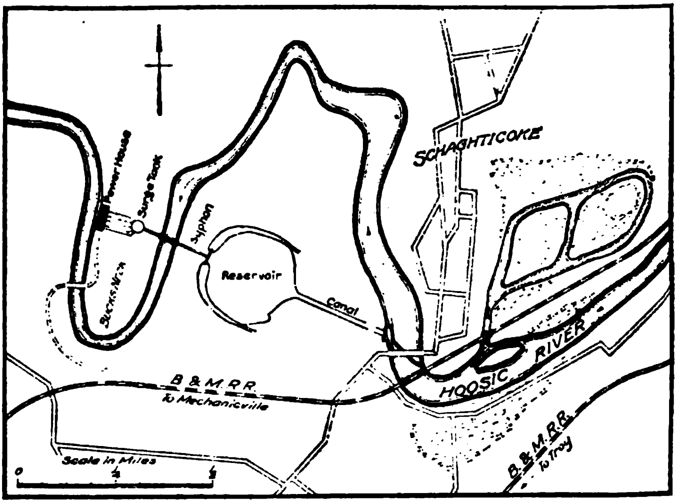

FIG. 210.—Map showing development on the Hoosick River at Schaghticoke.

leads to the smaller reservoir above-mentioned, distant about a half mile. This is really the forebay for the penstock intake. A large single steel penstock 12.5 feet in diameter, leads from this forebay to a surge tank situated in a cut in the crest of the hill. But to reach this point it must cross the river, because the complete "*S*" of the stream is to be developed.' In order to avoid heavy and unnecessary expense, the pipe is not maintained at uniform level, but is laid as an *inverted siphon*, carried upon concrete piers to which it is firmly anchored. The surge tank is 40 feet in diameter and rises about 56 feet. It is constructed of steel and varies in thickness from 9/16 inch at the base to 3/8 inch at the top.

From this point, 4 large penstocks 6 feet in diameter and 1 small one 2 feet in diameter are led to their individual water wheels. The small pipe is for the exciter units. The descent is quite steep, giving a head of about 150 feet with a pipe line of approximately 350 feet length. The control gates are located at the entrances of the penstocks, inside of the surge tank, and sudden closure effects no rise in pressure in the pipes themselves. They are electrically operated from the power-house or hand-operated from the surge tank. The exciter penstock is not thus designed but is hand operated at the power-house.

The water turbines used are of the vertical Pelton-Francis type, before described.

Governors.—One of the most important items of a water-power plant is the provision made for the speed regulation of the turbines. Variation in speed is accountable for variation in the voltage of the generator as well as in the frequency. These eccentricities will give instability of apparatus in receiving circuits and must be reduced to a minimum. The governors are operated by various means as oil pressure cylinders, water pressure cylinders, and mechanical devices.

The work done by a governor consists in adjusting the gate opening to that value required for the immediate load, or deflecting the nozzle of an impulse wheel. In general, they depend upon a change from the proper speed in order to be brought into operation. They therefore tend to limit speed variation and restore normal speed rather than to maintain an absolute value.

Numerous governors are on the market which will give full gate opening or its reverse within 1 or 2 seconds.

In choosing a governor the first thing to decide upon is the type. This will depend upon the mechanism used for gate operation, the range of angular movement required of the shaft, the individual preference as regards manufacturer, etc. The size of the governor will be determined by the amount of work it has to do in moving the gate through its complete range. The hydraulic unbalance upon the gate, the friction of gate and operating mechanism, all must be met. If the gate is installed the proper procedure is to measure the maximum pull required upon the hand-wheel at any point of gate operation, to measure

the lever arm and to count the number of complete turns of the hand-wheel for full operation. We then have,

p = maximum pull in pounds.
r = radius arm in feet.
n = number of turns.
$2\pi\ prn = W$ foot-pounds, work to be done.

The governor should have about twice this rating in order to provide for a suitable margin.

When these measurements cannot be taken—as before the construction of the plant—it is necessary to estimate upon the work to be done. This is no simple matter because of the impossibility of determining friction, etc. A comparison of data with those of other installations of similar features is about the only way to estimate this requirement. Full data should be sent to the manufacturer in order that he may be enabled to choose the proper size of governor.

As regards typical conditions, the makers of the Sturgess governors specify operation as below.

1. Complete range of gate in 1.5 seconds.
2. Under *gradual* change of load, regulation within 0.75 per cent. of normal.
3. Under *sudden* change of load, prompt regulation beginning before speed has varied 0.75 per cent. from normal.
4. No racing.

This latter term (*racing*) corresponds to the term *hunting* as used in reference to electrical machines. The water wheel does not immediately respond to a gate adjustment and the governor may tend to overreach. This would demand a second change in gate opening which would again overreach but in the opposite direction. This tendency must be counteracted by dashpot or some such compensating device.

A governing system should be powerful, sensitive, deadbeat, sturdy, and simple. The mechanism is constantly in operation and the utmost reliability attainable should be possessed.

There have been developed two widely used types of governors, the mechanical and hydraulic. In the former, the actions are wholly carried out by the use of interacting mechanical parts. In the hydraulic type, the pressures are transmitted from one

point of the device to another, by fluid pressure. In both of these types it is customary to depend upon fly-balls to originate the corrective effort. But as they exert only a very small force, they cannot act directly upon the turbine gates. They must, in both cases, act upon at least one relay which, in turn, controls a power sufficient to operate the gates. Anti-racing devices are a necessity.

The fluid type of governor is most common. It is built by several different manufacturers. Essentially, it consists of a

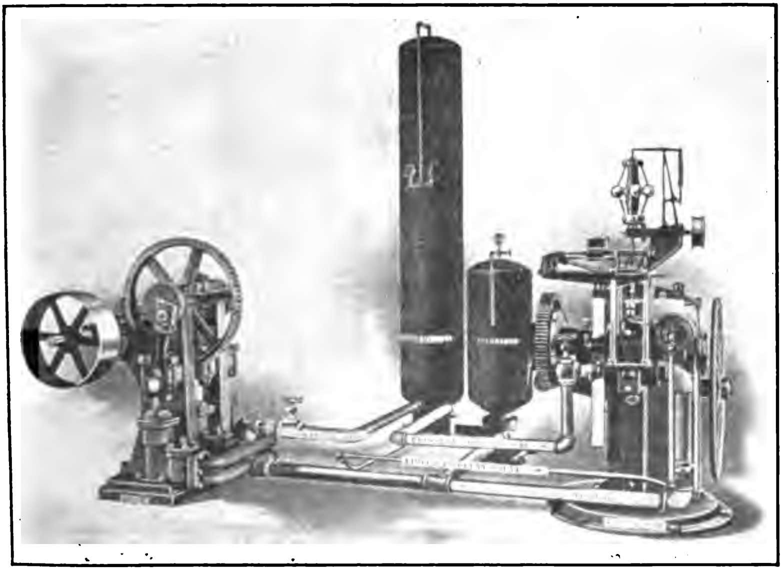

Fig. 211.—Lombard water wheel governor, type N.

power cylinder to operate the gate, controlled, perhaps through a relay, by fluid pressure brought into action by the operation of the fly-balls. The fluid pressure is maintained in a pressure tank by a pump which returns the used fluid from a receiver tank to the pressure tank.

The relay valves used are piston valves of a register type (Lombard) or poppet valves (Sturgess). Advantages claimed for the latter are that there is no lap and the closure is perfect.

The general details of a powerful Lombard governor may be

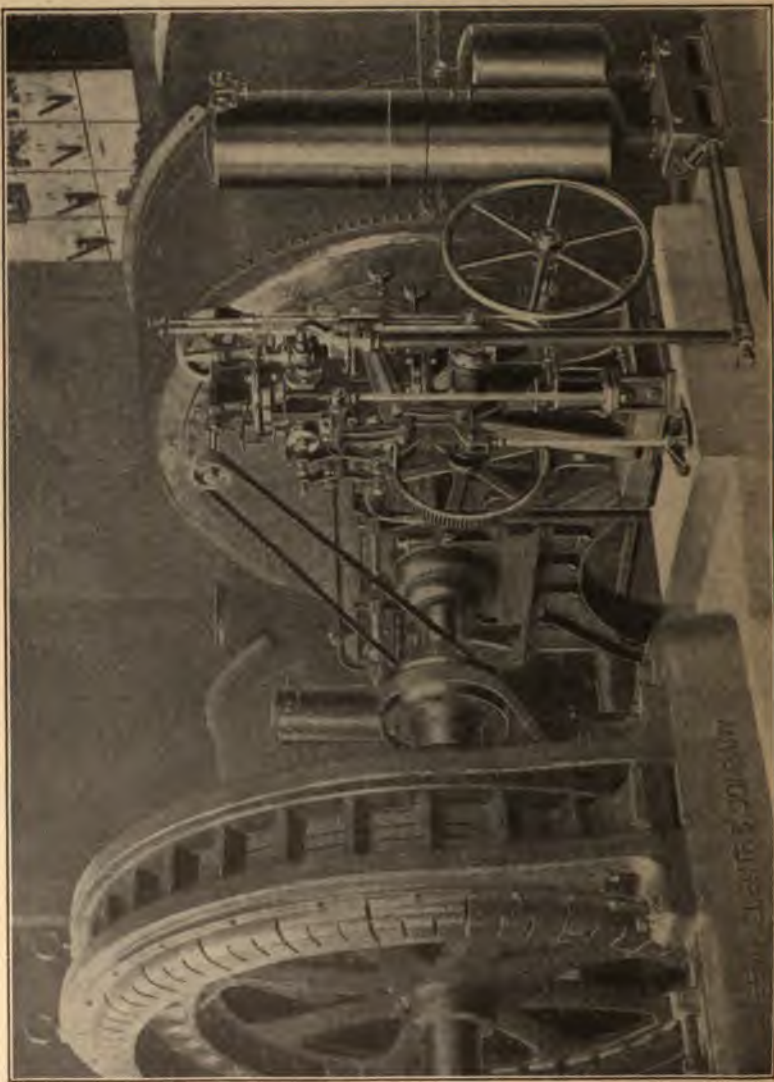

FIG. 212.—Sturgess water wheel governor, S. Morgan Smith, turbine; General Electric alternating-current generator.

seen in Fig. 211, where the principal parts are labeled. The assembly may be altered, inasmuch as it depends only upon proper piping from tanks to pump, cylinder, etc. In smaller sizes the tanks are often placed horizontally under the framework built to support the pump and valve mechanisms.

The method of installing such a governor may be seen by reference to Fig. 212, which is a view in the plant of the Rochester Railway and Light Company. The installation combines S. Morgan Smith turbines, General Electric generators, and Sturgess governors.

By way of comparison between the regulation or control secured with water-wheel or steam engine, Fig. 213 shows two

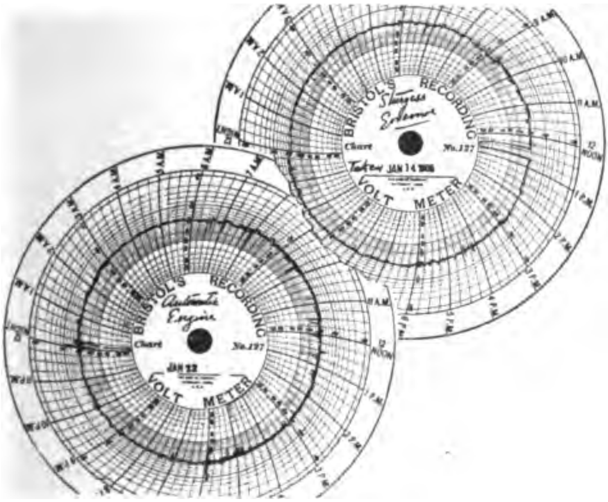

FIG. 213.—Comparison of voltage regulation with water-wheel drive and steam-engine drive.

charts, the one representing the voltage record for a 24-hour run of an automatic steam engine, the other an equal run of a water wheel with a Sturgess governor. Loads were the same for the two records.

In the mechanical type of governors, the fly-balls may operate a friction clutch which then serves as the medium through which to pass the effort of the main operating mechanism. In the Woodward governor, these friction faces are pan-shaped, two

being opposed to each other in mounting with a friction wheel between (inside) them. This friction wheel is raised or lowered by the action of the centrifugal ball system and the gate action depends upon which friction pan is energized.

In the Pelton type of wheel, the governing is often accomplished by a deflection of the nozzle instead of a reduction of water flow. This constitutes a difference in detail of the governing system, or a change in its method of application.

When rapid gate action is necessary, a correspondingly rapid change occurs in water velocity in the penstock. If the gates suddenly close, the impulse of the body of moving water must be met effectively by some means or destructive results may be frequent. This cannot be accomplished by increased strength of construction alone, but is taken care of by putting in relief valves, overflow stand pipes, etc. The overflow may be at the top of a vertical pipe or it may be over the crest of a high point in a waste tube.

In all water-wheel governing, there is necessarily present a time lag due to the necessity of overcoming the momentum of the moving water column. The steam engine governor has not this limitation. With the water wheel, a decrease in load is quite satisfactorily handled by the use of by-pass, stand-pipes, etc., but with increase of load the difficulty of starting the water column has no alleviation.

Steam Power.—Although the conversion of mechanical energy into the electrical form is accomplished with a very satisfactory efficiency, the change from heat energy to mechanical energy is quite the opposite. The change occurring with combustion of fuel releases the potential chemical energy in the form of heat or molecular energy. The efficiency of this step depends upon the completeness of the combustion, and, in general, may be considered as high. It will be seen, however, from subsequent discussions, that a considerable part of this may be lost if the principles governing complete combustion are neglected. After combustion, only a part of the heat energy reaches the machine or engine devised for the transformation to energy of mechanical motion. This is one of the low-efficiency steps. The loss of available heat energy reaching the engine is, again, notoriously bad.

An excellent illustration of the condition is seen in the carefully analyzed report of Mr. H. G. Stott (A. I. E. E., Vol. XXV) upon the economics of a certain power plant in New York City. The summary of losses is given in Table XXVII and shows distinctly the two inefficient steps, at the boiler and at the engine.

Table XXVII.—Analysis of the Average Losses in the Conversion of One Pound of Coal into Electricity.

	B.t.u.	Per cent.	B.t.u.	Per cent.
1. B. t. u. per pound of coal supplied...	14150	100		
2. Loss in ashes....................	....		340	2.4
3. Loss in stack....................	....		3212	22.7
4. Loss in boiler radiation and leakage.	....		1131	8.0
5. Returned by feed-water heater	441	3.1		
6. Returned by economizer...........	960	6.8		
7. Loss in pipe radiation.............	....		28	0.2
8. Delivered to circulator.............	....		223	1.6
9. Delivered to feed pump............	....		203	1.4
10. Loss in leakage and high-pressure drips............................	....		152	1.1
11. Delivered to small auxilaries........	....		51	0.4
12. Heating.........................	....		31	0.2
13. Loss in engine friction............	....		111	0.8
14. Electrical losses..................	....		36	0.3
15. Engine radiation losses............	....		28	0.2
16. Rejected to condenser.............	....		8524	60.1
17. Delivered to house auxilaries.......	....		29	0.2
Totals...........................	15551	109.9	14099	99.6
Delivered to bus bars.............	....		1452	10.3

It is seen that the grate and boiler losses consist of three parts, 2.4 per cent. lost in ashes, 22.7 per cent. loss in stack by hot gases, and 8 per cent. lost in boiler radiation, etc. Of these, certain parts are returnable by use of feed-water heaters and economizers. The heat absorbed by the air of the boiler room is also effective in raising the temperature of the air entering the combustion chamber. The greatest loss, however, occurs in the amount of heat rejected to the condenser, 60.1 per cent.

of the total. The electrical losses represent only 0.3 per cent. This is exceptionally low.

It follows that high economy has more to worry over in the losses of the first stages of the process of electrical generation than in the last one and an analytical study of the conditions existing in practice confirms the opinion that increased economy must come principally from the study of some of these especially unsatisfactory steps.

The area of air opening in grate surface is one of the important points in connection with the proper conditions for complete combustion. It varies with the kind of fuel used, depending upon the size of the coal and its liability to clinker. The thickness of the bed of coal upon the grate also depends upon these same things. Air supply may be by natural draft due to the height of a smoke stack, or a blower may assist either to increase pressure in the ash pit or to help to exhaust in the smoke passages. Careful firing is the only kind that should be allowed and a competent fireman at the boiler is of prime importance. Generally speaking, mechanical stokers assist in a betterment of results obtained. This seems to be true especially with the lower grades of coal as fuel. The more expensive hand firing may pay for itself with the coals of greater cost.

As an instance of what may be accomplished by careful firing, a case cited in the Engineering Magazine of October, 1910, is a good example. In a test conducted to show the possibility of smoke prevention, the regular fireman was allowed to fire for the first set of readings, without special instructions. Complete data were taken in order to be able to determine efficiencies as well as smoke prevalence. The second run was made with the fireman directed as regards his work, giving the condition equivalent to expert firing. The figures given below are a part of the conclusions reached. For the very decided improvement in smoke conditions, the reader is referred to the original paper.

	1st.	*2nd.*
Equivalent evaporation per pound fuel (f. & a. 212°)	9.22	10.9
Equivalent evaporation per pound combustible (f. & a. 212°)	10.54	12.2
Brake horse-power	647.0	690.0
Efficiency of boiler and grate	67.5	81.0

This indicates a saving of about 25 per cent. in fuel, which would give about \$1500.00 as the annual cash saving, if fuel is about \$1.50 per ton.

The carbon dioxid recorder has proved to be of considerable assistance to the fireman. In its various forms its object remains the same. It is designed to analyze the escaping furnace gases to the extent of determining the content of CO_2 and making a record of the amount found. The fireman should know what record would correspond to complete combustion of the fuel to CO_2 with no CO and no excess of air. With the recorder arranged for easy inspection the workmen are able to find out definitely how much improvement is possible. If they are familiar with the use of the indicator, it is especially effective, although even the inexperienced men will be enabled to profit by it. Of course, the percentage of CO_2 in the flue gases which would indicate the complete combustion of the coal must be determined by the analysis of the fuel.

The depth of the fire-bed also varies for different kinds of fuel. The distance from the surface of the fuel to the boiler surface depends upon the height of the flame as it reaches upward from the coal, which, of course, is only another way of saying that it depends upon the fuel and draft. It also depends upon the kind of boiler used and the most efficient point of application for the heat.

It will be seen that the starting of a new plant may be a series of tests upon it, using different grades of fuel, processes of firing, depth of fire-bed, etc., with a view to finding out the most efficient combination for subsequent operation.

The boiler may be either *water tube* or *fire tube*. In order to give a sufficient boiler surface for the absorption of heat from the gases, the ratio of boiler surface to grate area should be in the neighborhood of 36 for anthracite coal and 50 to 60 for bituminous coal. This means a subdivision of the boiler body into numerous tubes and these tubes may be arranged to contain the water, or they may be surrounded by water and themselves admit the heated gases. The water-tube boilers are safer from collapse and explosion and are generally used for the higher pressures. They are more expensive, however, than the fire-tube boilers.

Boiler efficiency is the ratio between the heat per pound of fuel utilized in heating and evaporating water to the total heat of the fuel. For a fuel having a calorific value of 14,500 British thermal units, full 100 per cent. efficiency would correspond to the evaporation of 15 pounds of water per pound of coal, as the latent heat of water at atmospheric pressure is 966 British thermal units. This evaporation is, of course, from and at 212° Fahr. If, then, a certain boiler requires 11 pounds of water per pound of fuel, its efficiency will be 11/15 or 73.3 per cent.

Boilers are given ratings in *horse-power*, although the unit does not mean the same thing as the horse-power rating of a generator or motor. There has been assumed as the unit the evaporation of 34.5 pounds of water per hour and the horse-power rating of a boiler will be the quotient between the total evaporation per hour and this unit figure of 34.5. This unit is one such that, if it is used as the basis of horse-power rating of a boiler, it is generally possible for the boiler to supply steam enough continuously to develop at the ordinary engine the rated mechanical power. With a very inefficient engine this could not be done, while with a very efficient engine it could be exceeded. Roughly, where anthracite coal is burned, the boiler will have about 12 square feet of heating surface per rated horse-power. The grate surface per horse-power will approximate the figure 1/3.

Feedwater heaters and economizers serve the same purpose of raising the temperature of the water before it is led into the boiler. This is accomplished in the case of heaters by using exhaust steam either directly or indirectly. This cannot bring the temperature of the feed water to the boiling point. The economizer utilizes the heat of the waste gases in the stack to bring the temperature to some high value, even above boiling (at atmospheric pressure). The value of the latter depends upon the temperature of the gases. To be especially effective, this temperature should be somewhat above that required to maintain the draft. The tubular construction of the economizer will leave gas passages between the cool water coils, but this will restrict the draft very appreciably. In the case cited above by Mr. Stott, the gain by the use of these accessories is given as about 10 per cent.

The *draft* required may be obtained either by natural or

artificial means. The former depends upon one or more chimneys, the latter upon steam jets or air blowers. For the higher pressures required with poorer fuels, artificial draft is necessary. In terms of the water column supported by the draft pressure, the draft may be expressed as equivalent to 0.5 to 1.5 inches of water. It depends upon the height of the chimney, the temperature of the chimney gases, the temperature of the external air, barometric pressure, etc. External temperature variations may be sufficient throughout the year to more than double the draft pressure obtained in hot weather. The draft must be sufficient even in the less effective periods to give pressure enough to force the boilers if required.

Artificial draft gives a greater flexibility and a more easily controlled condition. In power houses, it is applied by an exhaust blower in the stack or, less preferably, by pressure blowers at the ash pit. If installed after a plant has been in operation, it is more easily adapted to the pressure type. If installed at the time of the building of the plant, the exhaust type is feasible.

The *reciprocating steam engine* is more used than any other prime mover. It is easily and economically built in large and small sizes, is simple and economical in operation. From the standpoint of efficiency in the utilization of the heat energy supplied to it, however, it is extremely unsatisfactory because so much of this energy is carried to the exhaust. But to a considerable extent this is true of its competitors as well. The use of condensers can increase the range of temperature of exhaust from that corresponding to atmospheric pressure (212° Fahr.) to that corresponding to about 1 pound pressure (102° Fahr.). This gives about 33.5 British thermal units per pound of steam additional to that already derived from it in bringing its temperature down from its initial value. Suppose the initial pressure to be 100 pounds per square inch (the value of the initial cylinder pressure). The steam then represents 1181.9 British thermal units per pound. The range to atmospheric pressure gives us $1181.9-1146.6=35.3$ British thermal units. The range to a 2-inch vacuum or 1-pound pressure gives $1181.9-1113.1=68.8$ British thermal units, or almost twice as much heat energy as before. There is, therefore, much to be gained by lowering the

exhaust pressure beyond one atmosphere *provided new or increased losses are not excessive.* And this limitation is of the first importance in the reciprocating engine.

The volume of 1 pound of steam at 100 pounds pressure is 4.403 cubic feet. When this steam has been allowed to expand down to 1 pound pressure it will occupy 334.6 cubic feet. It is manifestly impossible to provide a cylinder which can cover so wide a range of volume. Indeed, even when we restrict the expansion to a range permissible as regards volume, we may reach uneconomical conditions of condensation within the cylinder due to the large amount of comparatively cool cylinder surface. For simple engines the vacuum should not be lower than 8 or 10 pounds pressure. The range of expansion of steam within a cylinder is limited, therefore, first by the excessive volume demanded for low pressures and its accompanying large friction losses and, secondly, by condensation losses.

The first step for relief of this difficulty is to use more than one cylinder. Partial expansion occurs in the high-pressure cylinder and the expansion is completed in one or more cylinders occurring later in the series. The compound engine results and it may be economically operated over a wider range than can the single cylinder (simple) engine. It may carry expansion down to 1.5 to 2 pounds pressure. Moreover, the compound engine may receive steam at as much as 50 per cent. higher pressure than the simple engine, thus increasing the pressure range by extensions in each direction.

Typical steam consumption for various types of reciprocating engines will be found in Table XXVIII. These data indicate that water rate decreases with increase of rated speed of engines; that condensers lower by 20 to 30 per cent. the specific consumption of the engine; that compounding also decreases the consumption. The values given are based upon the indicated horse-power of the engines and are only general. Naturally, the size of the engine will determine the applicability of compounding or condensing.

Hence, to contrast as is sometimes done the water rate of a simple, slide-valve, non-condensing engine with that of a large, compound, condensing, Corliss type of engine is not enlightening. They are not in the same class. No one would replace a 100

horse-power engine by a 1000 horse-power unit. A steam engine running at normal load or most economical load is at least a fairly satisfactory unit as compared with other prime movers to be discussed later. But when load fluctuates considerably, as is so frequently the case with electrical systems, the specific consumption varies toward poor values and, what is also serious, the change in steam volume per stroke necessitates expansion to lower pressures and temperatures and the cylinder walls and piston face are cooled, to be heated by the next greater charge. Condensation losses become serious.

Table XXVIII.—Water Rates for Steam Engines.

Type of Engine.	Low speed.	High speed.
Simple, slide-valve non-condensing	38	33
Simple, slide-valve condensing	24	19
Compound, slide-valve non-condensing	27	23
Compound, slide-valve condensing	21	18
Simple, Corliss non-condensing	25	
Simple, Corliss condensing	19	
Compound, Corliss non-condensing	22	
Compound, Corliss condensing	16	

It will be well to point out that there are more ways than one to rate an engine and that in comparisons between it and other prime movers, care must be exercised in seeing that they, too, are rated upon the same basis.

A prime mover and its generator combined offer the possibilities of receiving ratings in terms of *indicated horse-power* (i. h. p.), *brake horse-power* (b. h. p.) or *horse-power or kilowatt output*. In the case of the steam engine, the first method is most easily applicable and is most generally used. The rating thus adopted shows the horse-power represented by the steam in the cylinder as calculated from the indicator card. It is not output of the engine and thus does not include the mechanical efficiency of the engine. When this latter engine loss is included, the rating, derived from tests at the engine pulley, is called the brake horse-power. If, to the losses now included, we add the losses of the transmission system to the generator (belt, shafting, etc.) and

the losses in the generator, we are prepared to state the kilowatt output of the set as received at the bus bars. As an example, steam turbine-alternator units are more easily rated in the last manner. There is no "cycle" of operations corresponding to the stroke of the engine with the opportunity of measuring the work done in such a cycle. In our comparisons, these facts must not be disregarded.

Speed variations of a steam engine are of two classes, the change due to a change of load and the variation in angular velocity during one revolution, due to the non-uniformity of the driving force.

In order that generators shall properly divide their load when running in parallel, their engines must have drooping speed characteristics. Engines thus governed will maintain a proper balance. If their speed curves should rise with increased load, the result would be an attempt upon the part of each one to assume the whole load.

Speed variation per revolution causes a corresponding voltage variation of the generator. This is not allowable beyond certain close limits because of harmful effects in the load circuits, such as flickering lights, hunting of synchronous machines, etc. The engine builders are willing to guarantee not over 2 per cent. variation and this is quite generally acceptable.

Steam Turbines.—In the steam turbine we have a quite recent development of the prime mover, one which, in fact, is taking the hitherto undisputed place of large reciprocating engines in all electric generating stations. The large engine of a 1000 kilowatt unit is not nearly as common in recent installations as in the earlier ones. Instead of having successive charges of steam and allowing these charges to expand behind a piston and then discharge into exhaust, the steam is allowed to expand from boiler pressure continuously and to exert its propelling force upon blades of a wheel prepared to receive it. The motion may be due to the reaction upon the blades or to the impulse of the steam. The so-called reaction type of steam turbine may be recognized by the fact that in it the steam expands in the blade passages of the moving member. In the impulse turbine such expansion does not occur, but it is limited to the stationary passages called nozzles. That is, in the reaction type, pressure falls during the

passage of the steam through the moving member as well as through the stationary member (guide) passages. In the impulse turbine, the pressure falls in the nozzle passages but remains constant in the blade passages. The stationary members and the moving members have, for the two types, the general shapes of blading as is shown in Fig. 214. As will be recognized from the shapes of the blades, end thrust will be present with reaction machines but not with impulse turbines.

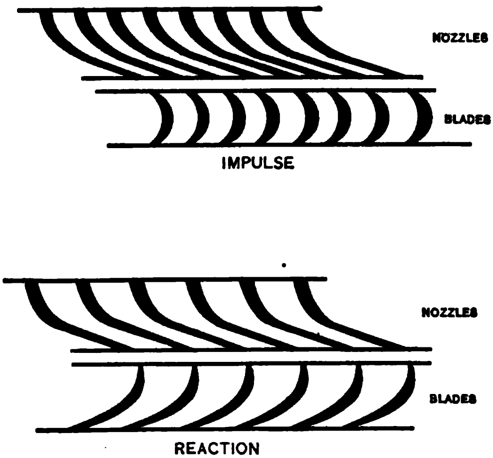

Fig. 214.—Steam turbine blading.

A simple or single-wheel turbine will consist of a set of steam nozzles opening upon the wheel passages, the steam passing to exhaust after leaving the moving element. The use of several sets of moving blades, alternating guide vanes with wheel vanes, gives a more practicable form for general construction and application. The simple impulse type is seen in the De Laval turbine. The compound-impulse type is represented by the Curtis, the Rateau, the Riedler-Stumpf, the Zoelley, etc. The principal representative of the compound-reaction turbine is the Parsons in its various forms. The best known of these different types in America are the De Laval, Curtis, and Parsons types.

The De Laval turbine, being a simple or one-wheel unit, is essentially a high-speed machine. In all turbines, the energy of pressure of the steam is first converted into kinetic energy of velocity and then transferred from the steam to the wheel by

reaction or impulse. If, then, the complete expansion must occur in one step, as in a single-nozzle impulse wheel, the steam velocity becomes enormous if initial pressure is near the ordinary values. Such velocities may reach as high as 4000 feet per second, or more. This shows why the De Laval turbines have such high speeds as 20,000 to 30,000 revolutions per minute for small machines with peripheral speeds as high as 1380 feet per second.

The Curtis turbine allows partial expansion of steam in its first set of nozzles, after which the steam passes successively through alternate wheels and guides; a second expansion is provided for in a second set of nozzles which is again followed by the alternate moving and stationary members. This process is repeated until the pressure energy of the steam has been transformed to velocity energy and the latter has been reduced to an amount just sufficient to carry the steam out of the passages to exhaust. The high velocities of the simple turbine are avoided. These steps can be illustrated by the case of a 6-stage 3500 kilowatt turbine in which, as built by the General Electric Company, with an initial pressure of 188 pounds, the successive expansions give pressures of about 66 pounds; 31 pounds; 12.6 pounds; 5 pounds; 2.12 pounds; 2.1 inches vacuum. Frequent rotational speeds for various sizes of this type of turbine are as follows:

Generator rating in kilowatts.	Speed in revolutions per minute. 60 cycles.		25 cycles.
500		3600	
750		3600	
1000	1800		
1250	1800		
1500			
2000			1500
2500			
3000			
3500		1800	
4000			
5000			
7500			
9000			
12000		720	750
15000			
20000			

The high speeds here met necessitate a small number of poles upon direct-connected generators whether of direct current or alternating current. The generator is always direct-connected, and for small units the shaft is horizontal, while for large units the vertical shaft design is followed.

The condenser is frequently placed in the base of the unit in order to economize in floor space. This gives a very satisfactory arrangement.

The Westinghouse-Parsons turbine, in which fall of pressure occurs throughout all its passages, requires numerous active

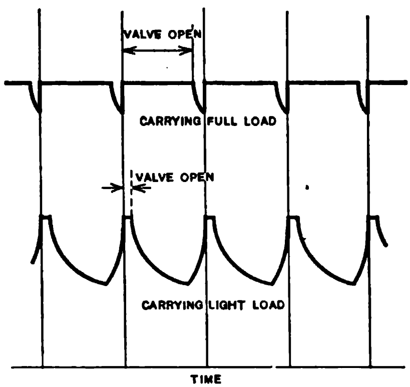

FIG. 215.—Parsons-Westinghouse steam admission for governing.

wheel vanes with alternate rows of stationary guide blades. As expansion occurs, the steam velocity must increase or cross-section of passages must increase. In fact, both events occur. The diameter of the revolving member is increased in steps and a larger number of blades are put upon each whirl. The end thrust is balanced by *balancing pistons* having the same effective diameters as each step in the blade series. The governing is accomplished by admitting steam in periodic puffs, the admission lasting a longer time with heavy load than it does with light load. The timing of the opening is determined by the fly-ball governor. The comparative results of such admission are shown in Fig. 215, where the flat crest of the wave shows the time the valve is open and an average ordinate would represent average initial pressure

at the first stage. With heavy overload demand, a second admission valve opens, allowing high-pressure steam to enter the second step of the turbine wheels.

This type is built with horizontal shaft, with direct-connected generator.

The Allis-Chalmers turbine is also of the Parsons type, but is different from the other machines of the same type in details of blading, balancing, end thrust, and packing of the balancing piston.

As mentioned in the discussion upon the steam engine, a vacuum is more successfully utilized with the steam turbine than with the engine. This is because the turbine presents practically unlimited room for the expansion of the steam. These volumes become too large for the reciprocating engines. It is quite possible to maintain a condenser vacuum at 28 inches pressure, a decrease in this figure indicating an increase in steam consumption of 6 to 3 per cent. for each inch lost, down to 23 inches.

The gain effected by superheating is more marked with the reciprocating engine than it is with the turbine. Owing to the low specific heat of steam, the actual addition of heat energy by steam is small. Its use, however, tends to eliminate condensation in the engine cylinder or turbine passages, with re-evaporation losses and friction losses. Moreover, in the turbine the water of condensation is not reversed in direction of motion in respect to the blade as is the steam, and hence does not approach an absolute speed (or discharge speed) of zero. It therefore does not efficiently give up its kinetic energy. With fluctuating loads, condensation is a very serious thing in the reciprocating engine while a variation in load does not increase it much in the turbine. The elimination of condensation is more important to the operation of the engine, but is also of great value with the turbine.

The economy curves for steam turbines are generally given in terms of pounds of steam per kilowatt hour at the switchboard. The figures given for large machines vary from 15 to 20 pounds, depending upon initial gage pressure, vacuum and superheat. Generally speaking, in large units of several thousand kilowatts, the economy of the reciprocating engine upon *steady, rated load* is in the same range as that for the turbines. The curves for engines rise more rapidly for light loads than curves for turbines.

Besides which, fluctuations of load, as in railway practice, will very materially injure the curve for the engine.

Figure 216 shows certain curves from data given by Mr. Stott (A. I. E. E., Vol. XXV) who concludes in his discussion that the two machines may be used together advantageously. The reciprocating engine would receive the steam, superheated and at high pressure, exhausting to the turbine intake at about atmospheric pressure. The latter machine would utilize the steam over the pressure range from atmospheric to 28 inches vacuum. Such a

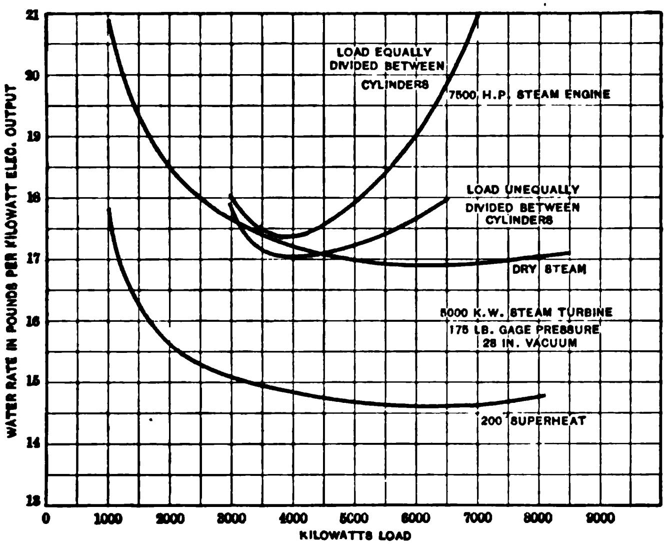

FIG. 216.—Water rate curves.

combination would (at about 5000 kilowatts each) give a water rate near 13 pounds per kilowatt hour. "This turbo unit would be interposed directly between the exhaust nozzle of the reciprocating engine and the condenser, and would have no valves or governing mechanism whatever. The generator would be connected directly to the other generator leads without any switching apparatus, except, possibly, knife switches to disconnect for testing purposes; and in operation no attention whatever would be required beyond the ordinary lubrication of bearings."

Since the above proposal was made (in 1906), several such installations have been made in this country and abroad. The

effect is well illustrated in the tests made upon an English plant which had previously been running non-condensing.

A condensing plant was installed at a cost of about $28.00 per kilowatt of turbine rating. A unique feature of the condenser is the use of sewer water for cooling purposes. It was found that the exhaust steam from two 780-kilowatt reciprocating engine-sets would supply one 1200-kilowatt turbine, the latter operating between atmospheric pressure and a 27.4-inch vacuum. In a three weeks' test, the saving effected was shown to be as follows:

	1908.	1910.	Saving.
Fuel	0.5 cents per kw. hr.	0.334 c. per kw. hr.	33.4%
Oil and stores	0.018 cents per kw. hr.	0.008 c. per kw. hr.	50%
Water	0.054 cents per kw. hr.	0.012 c. per kw. hr.	78%
Sal. and wages	0.108 cents per kw. hr.	0.094 c. per kw. hr.	
Repairs (est.)	0.114 cents per kw. hr.	0.114 c. per kw. hr.	
	0.796	0.562	30%

It will be noted that this figure does not take into account the increased interest on investment.

In another case, that of the Philadelphia Rapid Transit Company, a similar addition was made to the equipment originally consisting of compound, non-condensing Corliss engines. As boiler capacity was not sufficient to carry more reciprocating engines, low-pressure Curtis turbines were installed between the engine exhaust and condensers. With this condition the turbine will use about 40 pounds of steam per kilowatt hour. The results obtained indicate that, with complete installation, the output of the station should be increased by about 70 per cent. without increased steam consumption.

To further compare the operation of steam and gas engines and turbines, we will reproduce a tabular statement made by Mr. Stott in his paper before quoted. Table XXIX shows in the first column results for compound condensing reciprocating engines without superheat, derived from actual costs for a year's record. Load factor was about 50 per cent. The other columns are mainly estimates.

Internal Combustion Engines.—One of the quite modern competitors in the class of prime movers for electric generators is the gas engine or, more broadly, the internal combustion engine.

It appears in many forms, ranging through the use of illuminating gas, blast furnace gas, gasolene, kerosene, and even crude petroleum. Its principal shortcomings have been its speed variation during one revolution and the inability to carry much overload.

Table XXIX.—Comparison of Costs, etc., of Various Types of Prime Movers.

	Reciprocating engines.	Steam turbines.	Reciprocating engines and steam turbines.	Gas engine plant.	Gas engines and steam turbines.
MAINTENANCE.					
1. Engine room mechanical.	2.57	0.51	1.54	2.57	1.54
2. Boiler room or producer room	4.61	4.30	3.52	1.15	1.95
3. Coal and ash-handling apparatus	0.58	0.54	0.44	0.29	0.29
4. Electrical apparatus	1.12	1.12	1.12	1.12	1.12
OPERATION.					
5. Coal and ash-handling labor	2.26	2.11	1.74	1.13	1.13
6. Removal of ashes	1.06	0.94	0.80	0.53	0.53
7. Dock rental	0.74	0.74	0.74	0.74	0.74
8. Boiler room labor	7.15	6.68	5.46	1.79	3.03
9. Boiler room oil, waste, etc.	0.17	0.17	0.17	0.17	0.17
10. Coal	61.30	57.30	46.87	26.31	25.77
11. Water	7.14	0.71	5.46	3.57	2.14
12. Engine room mechanical labor	6.71	1.35	4.03	6.71	4.03
13. Lubrication	1.77	0.35	1.01	1.77	1.06
14. Waste, etc	0.30	0.30	0.30	0.30	0.30
15. Electrical labor	2.52	2.52	2.52	2.52	2.52
Relative cost of maintenance and operation	100.00	79.64	75.72	50.67	46.32
Relative investment in per cent	100.00	82.50	77.00	100.00	91.20

The *four-cycle* engine (in reality a four-stroke-per-cycle engine) is represented typically by the Otto cycle (Fig. 217). In this cycle the first intake stroke draws into the cylinder the charge.

The return stroke compresses the mixture of air and gas. Near the end of the stroke ignition occurs and combustion brings pressure up to a high value. This pressure then accomplishes the working stroke. Exhaust opens and the return stroke forces the gaseous products of combustion out of the chamber. The cycle is then repeated This means that there is only one

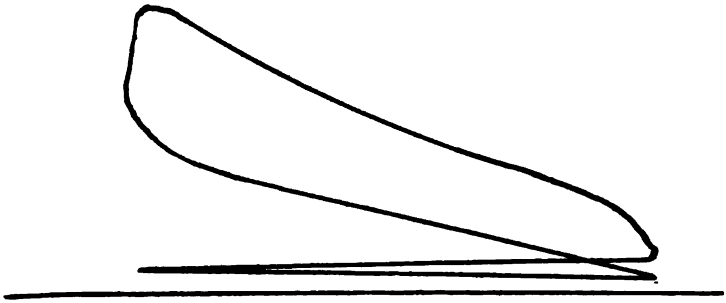

FIG. 217.—Otto cycle.

working stroke in four strokes, two revolutions, and the crank effort diagram will look like Fig. 218. Thus, a single-cylinder, single-acting (*i.e.*, four-cycle) gas engine gives a greatly varying crank effort.

We may, however, depart from this condition by either of two methods. First, we may multiply the number of cylinders and so time their epochs that their working strokes are evenly spaced

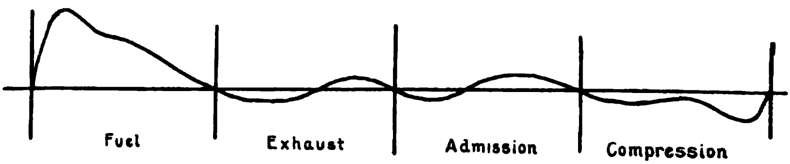

FIG. 218.—Crank effort diagram, Otto cycle.

over the time required for two revolutions. By such a construction, the turning effort may be kept within the proper limits for successful application to the electric generator. A second device is to use *two-cycle* operation, with or without multiple cylinders. In this process, the crank end of the cylinder is enclosed so that the working stroke may be utilized to compress therein the next

charge for the working chamber. Exhaust in the working chamber occurs just previous to the opening to admission and the latter helps to sweep out the last remaining burned gases, etc. This will give each revolution one working stroke and bring the cycle to an equality with that of the single-acting steam engine. The two-cycle engine is smaller than an equivalent four-cycle engine, as its individual working strokes are more frequent.

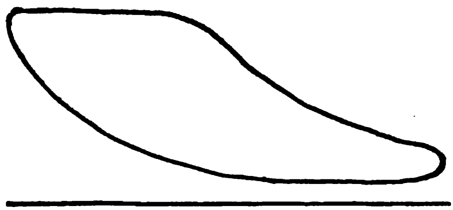

FIG. 219.—Brayton cycle.

Nevertheless, owing to the fact that intake and exhaust occur simultaneously, the efficiency falls rapidly with departure from the best load and the best speed of operation.

Besides the Otto cycle, there are other possibilities for the internal combustion engine. In this, it differs from the steam engine where the energy is developed in the cylinder at only one stage—admission. With the gas engine, however, combustion may occur at constant volume (Otto cycle), at constant pressure

FIG. 220.—Diesel oil engine cycle.

(Brayton cycle) or at constant temperature (Diesel engine). The latter two cycles are shown in Figs. 219 and 220.

In the Brayton cycle fuel is admitted and burned at about constant pressure, giving an indicator card very similar to a steam card. The Diesel engine, using liquid fuel, operates with no constant pressure or constant volume lines in its indicator card. Combustion occurs during admission, but at constant

temperature which gives an isothermal combustion line. In this cycle a charge of air is compressed to about 500 pounds per square inch and the liquid fuel is sprayed into the chamber. So high a pressure serves to raise the air temperature to a point where the oil is ignited immediately upon its entrance into the combustion chamber.

In economy of performance, the gas engine or oil engine has some decided advantages over the steam engine. A good slide-valve steam engine will utilize about 5 per cent. of the heat energy of the fuel. By changing from slide-valve to the type where exhaust is timed independently of the admission (the four-valve Corliss type) this economy may be increased to 6 per cent. Compounding and use of condenser brings it up to about 8 per cent. Triple expansion gives about 12 per cent. Gas engines of the explosion type may be expected to give 16 to 18 per cent. Oil engines, 18 to 20 per cent. Diesel engines about 30 to 35 per cent. These figures are based upon the indicator cards and must be lowered to represent output at the shaft or pulley and it must be remembered that the gas engine has high thermal efficiency and low mechanical efficiency, while the steam engine reverses these characteristics.

As regards overload capacity, the internal combustion engine is at a disadvantage because its action is best at normal intake with normal mixture of air and gas or other fuel. An overload demands more fuel which in turn demands more air for combustion. But the capacity of the cylinder remains the same and no great excess in charges may be attained. If, then, the machine is to be capable of taking much overload, it must be underrated and run rather uneconomically at normal load.

The capacity of a gas engine is different for different altitudes. This is because the amount of air per cubic foot depends upon altitude, and, with lighter weight of air intake, the charge of fuel is necessarily decreased, thus lowering the output.

The principal advantages and disadvantages of the internal combustion engine may be named as follows:

Advantages:

1. The pressure due to the heat energy is developed in the engine cylinder where it is used and no wastes occur, corresponding to the losses of the boiler, smoke stack, etc.

2. The engine is easily and quickly started.

3. A considerable storage of fuel is possible in the form directly used by the engine. The space required for it is small.

4. Fuel handling is easy and operation is cleanly.

5. With oil engines or where gas is purchased, the system has no complication corresponding to the boiler plant and is very simple.

6. Fuel is cheap.

Disadvantages:

1. The crank effort is irregular, and the maximum pressure in the cylinder is high for a given mean value. A fly-wheel is necessary.

2. Auxiliary apparatus is required for starting.

3. The overload capacity is quite restricted.

4. There is no energy storage in its usable form, as in the case of steam. Power for each stroke is developed just as it is used. (Compare advantage No. 3.)

5. There is no range possible below atmospheric pressure (as with condenser).

6. Governing is not easy to accomplish nor are replies to governor action prompt because of the infrequency of the working stroke.

7. There are numerous parts, the failure of any one of which will stop the engine.

As regards the cheapness of fuel for gas engines, considerable might be said. Natural gas regions may be recognized at once as favorable localities for the use of such engines. If coal is cheap—poor grades and short haulage—producer plants may be established and gas generated for use. The producer is a very satisfactory piece of apparatus and will give to the gas about 82 per cent. of the energy of the coal. Low-grade fuel may be used with it. In oil engines there may be used some of the cheaper grades of oil. The Diesel engine will use crude petroleum and has been known to run, experimentally, using fine coal dust as its fuel. Its makers guarantee 1 kilowatt hour at switchboard with use of 7/8 pound of crude oil. Alcohol has been little used here in America, but with the recent reduction in price due to removal of the revenue tax, the engine will probably be developed to a greater extent for small units.

Gas and oil engines will cost in the neighborhood of \$50 per horse-power for sizes of 50 to 100 horse-power. For special installations they are built in very large units, the 2400 horse-power blast furnace gas engines of the Indiana Steel Company at Gary, Ind. being examples. For richer gas the units may be more powerful and smaller as, for instance, the 4000 horse-power gas engines of the California Gas and Electric Corporations.

Electrical Generators.—Generators for converting the mechanical power of the prime mover into electrical power may be connected to the latter by mounting upon a common shaft, by belting from pulley to pulley, by rope drive, by gearing, etc. The first two of these, direct-drive and belt-drive, are by far the most common. Generally speaking, the choice between the two is determined by the ratio between the individual economical speeds of the two machines. If both prime mover and generator may be built for the same speed without much sacrifice in efficiency, without too great increase in cost, etc., it is proper that they should be mounted upon a common shaft or otherwise connected for direct-drive as may be best suited to the type of prime mover. With water wheel and steam turbine the common shaft is practicable. With reciprocating engines, steam or gas, the crank shaft drive is required.

Rope drive and gearing are of limited use, although they may be included within the scope of good practice and may each have special applications where it becomes valuable. An instance of this is where the high-speed De Laval turbine is to be connected to a generator. Here we have speeds of prohibitive value for the generator or even for pulley- and belt-drive. The problem is solved by the design of high-speed gearing. It may run at peripheral speeds as high as 6000 feet per minute. In order to insure proper meshing of teeth of pinion and gear, it is customary to assemble the generators in pairs, letting one turbine drive the two. The pinion of the turbine shaft drives two gears, one upon each side. The lateral pressure necessary for high-speed work is balanced by this opposition. There is no great increase of friction because of side pressure upon the turbine bearings nor is there liability of interference because of bending the shaft. If only one electric circuit is desired, the two generators may be connected in parallel if great care is taken to adjust their division

of load. Probably it is preferable to place them in series, both armatures and fields, so that they become parts of one machine. This is possible either with direct-current generators or alternating-current generators. Even polyphase machines may be so connected, leg by leg.

Rope-drive is suitable for distances too great for belting and especially for vertical transmission of power. The *rope sheaves*, as the pulleys are called, have great enough width to receive in their grooved faces a proper number of rope strands to transmit the power required. These strands may be either the continuous rope (American) or multiple rope (English). The former has the advantage of uniform tension, ease of installation, single splice, and the disadvantages of high original cost, expense of reserve and replacement, and shut-down in case of a single break. The latter system necessitates care in installation as regards tension, making of numerous splices or joints, but avoids excessive reserve material or complete failure for one break.

Direct connection between driver and generator is sometimes accomplished, as pointed out, by pressing the moving member of the generator upon the crank-driven engine shaft, the turbine shaft, etc. Again, the shaft of the generator may be coupled to that of the prime mover by rigid flange coupling, flexible coupling, or even friction clutch. Of these several possibilities the assembly upon driven shaft and the flange coupling are the ones most suitable for heavy work and general installation.

By far the greatest part of alternating-current electric generation occurs with polyphase machines. The economy of electric transmission is served by use of three-phase circuits. It is much more satisfactory and economical to generate thus than to lose in efficiency by a transformation from some other form. Inasmuch as there is generally a considerable part of the power utilized at some point other than that of generation (and sometimes all of it) the importance of the polyphase alternating-current generator is apparent. Furthermore, the polyphase generator is a simple machine to operate, it is comparatively inexpensive and its reliability is high. It is a sturdy machine capable of carrying overloads satisfactorily.

Formerly, it was built with a stationary field and revolving armature. The construction is greatly simplified and strength-

ened by placing the armature winding in slots upon the nonmoving member where insulation and dynamic strains are more easily taken care of and placing the field poles upon the revolving member. The field construction does not include the distributed winding except in special forms. It is, hence, quite possible to cause the centrifugal strain upon the field conductors to be taken by the iron pole tips, giving greatly increased strength. Where the *round rotor* is used and the field winding must be distributed, the slots are few and large and the strains are more easily met than in an armature winding with heavy end connections. With increased voltages of to-day, the ease of insulation of stationary armature presents the greatest gain, because the insulating materials used do not add mechanical strength to the armature coil at all comparable to the increased volume or weight.

Field excitation will require from 1.5 to 5 per cent. of the kilowatt rating of the generator. This varies considerably with the rated speed of the machine. With a certain voltage it may take 2 per cent. If, now, the voltage remains the same, but speed is reduced, an increase in field flux is necessary. The kilowatt rating of the exciter would, therefore, be increased. As an example, a certain 650-kilowatt generator running at 90 revolutions per minute required for excitation a 30-kilowatt machine. A similar generator running at 600 revolutions per minute was found to need only a 9-kilowatt exciter. The number of poles is reduced from 80 to 12 by the change in speed (60-cycle machines) and the decrease in length of field winding and its resistance affect the rating of the exciter more than does the increased length of magnetic path. The densities may have changed, also.

The older type of *inductor alternator* is not as common as it was formerly. In it the revolving member moved within an immense stationary bobbin which contained the field winding and magnetized the rotor in an axial direction or crosswise. The polar projections upon this field coming in front of first one set of coils and then another serve to give maximum flux cutting and then zero cutting. But this is an uneconomical condition because, if the flux should be changed from positive maximum to negative maximum instead of maximum to zero and back to maximum again, a given voltage would require only half the flux

that is needed with the non-reversal of flux. The weight economy is, therefore, low, or cost is high. The great advantage claimed for it is the absence of revolving windings, as neither field copper nor armature copper moves.

The *efficiencies* of alternators are quite high. They depend upon the size of the machine, the speed, and the voltage. For large machines running at speeds most suitable to their sizes, efficiencies may be secured as high as 98.5 per cent. Either extremely high speed or low speed would have the tendency to lower this figure, although the effect of the latter is the greater. Typical efficiencies for normal conditions of voltage and speed are illustrated by Table XXX.

Table XXX.—Typical Alternator Efficiencies.

Load / Machine.		0.25	0.50	0.75	1.00	1.25
Size in Kw.	Speed in R. P. M.					
15	500	75.0	84.0	87.0	89.0	89.6
50	900	78.0	86.0	89.0	91 0	91.5
100	900	84.0	90.5	93.0	94.0	94.6
150	500	85.0	91.2	92.3	93.6	93.8
300	300	86.2	92.2	94.0	94.8	95.3
1000	300	88.0	93.0	94.6	95.3	96.0
2000	300	89.0	93.8	95.5	96.0	96.6
5000	250	90.0	94.0	95.8	96.5	97.0

Regulation of a constant potential machine is defined by the A. I. E. E. as being the ratio of the maximum difference of terminal voltage from rated load value to rated load terminal voltage. The range of load is from rated load to open circuit. That is, the greatest variation from rated load value of voltage is noted as the load is changed over the range mentioned—full load to no load. This variation, divided by the rated load terminal voltage, gives the decimal representing the regulation of the machine. Generally speaking, the regulation of a generator is of considerable importance. If it exceeds a certain amount,

depending upon the nature of the load, the voltage variation becomes so great as to introduce serious difficulties to proper operation. A lighting load should be supplied with energy through a generator having a good regulation, or the voltage fluctuations will cause very unsatisfactory operation of the lamps upon the system. Candle-power is very sensitive to voltage changes.

A regulation of not over 6 per cent. is asked for in generators for lighting service, but this is much too great to allow *at the lamps*. Voltage regulators may, however, maintain a proper degree of stability. For power load, the close regulation is not generally so important a point of operation and valves of 8 per cent. or more may be allowed.

The voltage of the generators will depend upon the power rating of the plant and the distance of power transmission. Where line voltages of less than 15,000 volts may be considered as suitable for the installation, it is possible to supply them directly from generator terminals. In fact, European practice goes up to 30,000 volts and American practice has reached as far as 20,000 volts. These are not typical of general practice, however, but represent, rather, the present extremes. Where potentials above 15,000 volts are desirable or required, the alternator potential will generally vary from one-third to one-sixth of the line pressure. For extremely high-line voltages the ratio may be increased. The most suitable balancing of line, transformer, and generator constants may be assumed to be in the general neighborhood of the one-to-five ratio of generator-to-line voltages. It is a fact, however, that high generator voltages are being persistently shunned because the factor of safety for insulation is much lower at the generator than at the transformer. Many large machines are being installed at 5000 volts or less on high potential transmission systems.

Speed ratings have a very decided influence upon cost of alternators. Slow-speed machines are more bulky per rated kilowatt both in iron and copper. Hence, the type of prime mover may influence price very considerably. The size of the unit likewise affects the cost. Large units cost from $12.00 down to $10.00 per kilowatt. Smaller machines will be more expensive. The cost of exciters for large machines will be in the neighbor-

hood of $1.00 per kilowatt of generator capacity. This figure increases with decreasing size of generator and for as small sizes as 50 kilowatt may be around $2.00 per kilowatt. Naturally, the price depends very materially upon the type of exciter used. That is, the belt-driven exciter is designed for its most economical speed, etc. It is necessary to provide parts for it which would not be included in an exciter mounted directly upon the same shaft as the generator. If the generator speed differs materially from the best exciter speed, a direct-connected exciter would be expensive, despite the fewer parts. With comparatively high speed generators this would lessen the difference or perhaps reverse the positions upon the scale of the two types of exciters.

This is, however, so small a part of the total cost of the installation, that it does not influence the choice between types as a general thing. Other things, as the availability of space, the symmetry of assembly, simplicity, etc., have more weight and determine the choice.

Self-excited alternators are not built in large sizes and they are considerably more complicated than are the separately excited machines. A perfect automatic regulator for field excitation which will take into account the power factor of the load, the variations in load, etc., presents many complications.

General alternator characteristics.—Armature constants, namely, resistance and reactance, affect the shape of the volt-ampere characteristic of the alternator. This was pointed out in discussing the regulation of the machine. But they are furthermore important in limiting the rush of current that occurs with short circuit of the armature. When short circuit occurs, the rush of current is eventually determined by the combined effects of the field, the armature reaction upon the field and the impedance of the armature circuit, of which the resistance is negligible compared to the reactance. At the first instant, armature reactance has not affected the result and the current rises to the value,

$$i = \frac{e}{x}$$

where e is the nominal generated voltage and x is the armature reactance. If, then, the value of x is small, as is the case of turbo-alternators, other alternators of very good regulation, etc.,

the value of current reached for the first instant of a short circuit may become enormous. There exists a secondary effect in the field circuit, also, causing a large rise of current there, with pulsating cycles. Both of these gradually decrease to their permanent values, unless there are line switches or breakers opened by the peaks, which ordinarily would occur if automatic protection is provided.

A three-phase alternator may have its armature coils connected Y or Δ. For high voltages the Y-connection is always preferable,

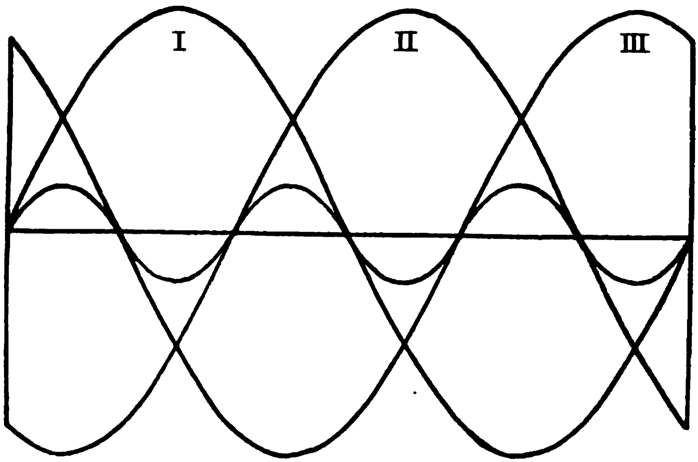

FIG. 221.—Three-phase triple harmonics.

inasmuch as it gives a lower voltage per leg. For low voltages, the Δ arrangement frequently occurs. If there is present in the electromotive force generated a triple harmonic, there is considerable difference in the results depending upon these armature connections.

If we look at the voltage curves for the three legs as shown upon rectangular coordinates, considering the waves as 120 degrees apart, the positive directions for the legs of the Y may be taken as outward from the common point. Figure 221 shows that a triple harmonic for one leg is in phase with that for each of the other phases. When the armature is connected Y these triple harmonics oppose each other because they are all away from the neutral point or all toward it simultaneously.

If a neutral tap is brought out and grounded and the load also has the same arrangement, there is a path provided for the triple harmonic of current and it will be present. With Δ connection, the triple harmonics are short-circuited in the armature and may become rather large. In either case, there is greater heating of the generator in case of the presence of these harmonics. A meter in the neutral or in the delta may show such currents present, though the most striking method of showing it is to take an oscillographic record, where the triple frequency is easily detected (Fig. 222).

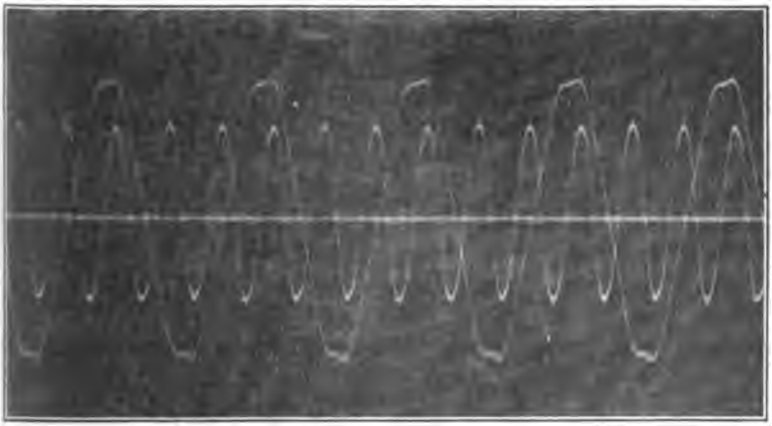

FIG. 222.—Short-circuited triple harmonic in delta-connected armature.

Alternators are generally of the polyphase type, as this gives more economical construction and transmission, as well as giving more satisfactory and flexible operating conditions. Where single-phase load only is required, as with lighting, single-phase railways, etc., the separate phases of a three-phase alternator may supply different portions of the load.

Direct-current generators are to be obtained in all sizes from the fractional horse-power to 1200 or 1500 horse-power. They are of the plain shunt type of field or of compound field winding. The nature of the load determines whether they are to be of the constant-current type or of constant-potential. The former would be used with direct-current series arc circuits, but this is

about its only application. To a considerable extent, the constant potential generators may be looked upon as the same machines as will be described more in detail under the head of motors in the chapter upon distribution.

The plain shunt generator will give a drooping voltage characteristic as load comes on, due to *ir* drop and armature reaction. The compound winding will compensate for any portion of this drop or over-compensate for it, if desired, maintaining constant potential at some distant point in the distribution. It will not give a straight-line variation between voltage and armature current or load. With proper setting for no load conditions and desired voltage at full load, the regulation between these two points upon the curve is not, therefore, exactly proportional to the load, but is slightly higher than it should be.

Speed has considerable effect upon the cost of direct-current generators as it does upon alternating-current machines. The cost may be as high as $30.00 per kilowatt for small sizes and may be taken as about $15.00 per kilowatt for large machines. The effect of increased speed is, naturally, a reduction in amount of material used, meaning reduced weight and cost. The multipolar construction also reduces weight and cost.

Efficiencies of direct-current generators vary from 75 per cent. with very small units to about 92 per cent. with large units. Their efficiencies are never as high as those of alternating-current machines, because of the presence of new sources of losses, as brush friction, commutator losses, etc.

Voltages run up to about 750 volts for the constant potential machines. Commutation troubles occur if this is pushed much higher. The use of compensating windings, however, will aid in the attempts to reach higher voltages upon generators and 1200 volts or more may be attained.

CHAPTER X.

TRANSMISSION.

The route of the transmission line must be selected, having in mind many features of construction, maintenance and operation. All other things being equal, the most direct route is preferable, because of the economy of material and labor. Seldom, however, are the conditions as simple and the choice as free as this. Frequently, even in comparatively short lines, the load carried is a distributed load, the elements of which do not lie even approximately in a straight line. The question then arises as to whether the line shall be direct with branches or whether it shall be laid out to reach directly the localities to be served. To determine the preference, not only must the length of routes be considered with the comparative costs of conductor, towers, right of way, etc., but there must also be studied the methods of control of branch lines, with switch houses and the possibility of attendants. Expense will not be the only thing to be given weight. If a certain customer demands a service without interruption, the installation must reach him with as much reliability as if he were upon the main line. For branch line service in this case, the switching must be done and the line controlled with the utmost dispatch. The branch will be as well served as the main line and may be looked upon as an integral part thereof.

On the other hand, if interruptions to service lasting ten minutes, thirty minutes, an hour, are not serious, the branch may be of much less expensive construction than the main line. Switching may be done by very different means, delay being unimportant. Protective devices will be less refined or perhaps wholly absent except in the most rudimentary form.

Certain routes may be laid out in such a way that the towers are placed at specially advantageous points, giving increased effective height of tower if placed upon a knoll or eminence, or giving exceptional strength of setting for an angle. With short spans and wooden pole lines, this point is not of great value, but

with steel towers, it gives individuality to each tower and its setting. Spans will vary in length and towers may be of different heights, although the latter condition is not necessary except for special work, nor is it very common.

Distinct differences may occur in the various possible routes in regard to character of earth and its suitability for supporting heavy towers. Rolling land gives much better and simpler construction than would low, swampy ground. Rocky ground will make expensive lines because of difficulty in securing proper footings. Two routes between the same points may present quite different depreciation rates. Exposure to storms, snow slides, or land slides is to be avoided. It is generally preferable to increase the length of a line somewhat rather than to carry it over a high point where it may be exposed to severe lightning disturbances, or through a deep valley subject to storms. Not the least important thing to consider is the accessibility of the route for construction and for maintenance. Hydraulic development must occur where the opportunity is given for it, and some of the locations of power stations are, thus, far from ideal. The transmission line has imposed upon it severe conditions because of this restriction and frequently they must be met by making the best of a bad situation.

Where two lines are to be paralleled, they may be allowed to follow different routes. This will give increased installation expense, but, in the case of precarious conditions of service, increased reliability is attained.

In taking up the problem of line calculation, two different problems will be assumed and various calculations made upon each.

Problem A.

To deliver 5000 kilowatts over a 50-mile, three-phase line. Power factor, 0.90.

Choice of Frequency.—Natural frequency of line $=\frac{47000}{50}=$ 940. Hence we may choose either 60~ or 25~, as the higher harmonics of neither fundamental wave can coincide with this value

and cause resonance. In order to avoid high reactive drop we will assume frequency of generating system as 25~.

$$f = 25\sim.$$

Choice of Voltage.—Standard voltages for transmission may be given as follows: 550, 1100, 2200, 4400, 6600, 13200, 44000, 66000, 88000, 110000, 140000.

Of these values, up to 13200 may be called low-voltage transmission if we assume as the dividing point the value which to-day may be obtained without the use of transformers. That is, at 13200 volts or below, the interposition of transformers between generator and line is not required, although it very often occurs..

Above 13200 volts we will term high-voltage lines; 20000-volt generators have been built in America but, not being common, at present we may ignore them in fixing this division point.

The step from 13200 volts to 44000 volts is large, and many lines use intermediate voltages. However, the region is critical in that the decrease in cost of line material may not equal the cost of transformers. If much benefit is to be derived, a fairly wide change in voltage is necessary. 140000 volts is merely a proposed standard yet to be attained, but its choice is even now a strong probability. Even 160000 volts is being considered.

Allowing approximately 1000 volts per mile of line, the voltage required would be 50000 volts. In order to give a value closer to a standard one, we may take the line voltage at receiver to be

$$E = 60000 \text{ volts.}$$

Current.—The line current becomes for unity power factor

$$I_0 = 48.2 \text{ amperes,}$$

while for the given power factor of 0.90 we have

$$I = 53.5 \text{ amperes.}$$

Line Loss.—As previously mentioned, the allowable line loss may be assumed at a value from 5 to 20 per cent., depending upon cost of power, etc. We will assume for this case about 12 per cent. loss. This means 600 kilowatt loss or 5600 kilowatt generated and supplied to the line.

Size of Conductor.—In order to select the size of conductor, find line constants, etc., we will first neglect charging current and calculate line resistance from permissible line loss.

$$i^2 r_1 = 600 \text{ kilowatts for three lines.}$$

$$600000 = 3(53.5)^2 r_1,$$

whence

$$r_1 = 69.5 \text{ for 50 miles.}$$

Choosing size No. 4 B & S. as a close value, we have

$$r_1 = 65.47 \text{ ohms for 50 miles.}$$

The weight of one conductor will be about 32,800 pounds figured at 0.32 pounds per cubic inch of copper, and not allowing for sag.

Spacing.—For a voltage as high as 60000 volts, we should choose at least 6 feet as the distance between lines.

Inductance and Inductive Reactance.

From the formula developed

$$L_{mi} = 0.0805 + 0.741 \log \frac{d}{r}$$

where d = distance between conductors and r = radius of the conductor,

$$\begin{aligned} L_{mi} &= 0.0805 + 0.741 \log \frac{72}{0.104} \\ &= 2.186 \text{ millihenrys.} \\ L_{50} &= 109.3 \text{ millihenrys} = 0.1093 \text{ henrys.} \\ X_L &= 2\pi f L = 17.2 \text{ ohms per conductor.} \end{aligned}$$

Capacity and Capacity Reactance:

$$\begin{aligned} C_{mi} &= \frac{0.03878}{\log \frac{d}{r}} = \frac{0.03878}{\log \frac{72}{0.104}} \\ &= 0.01365 \text{ microfarads.} \\ C_{50} &= 0.6825 \text{ microfarads} = 682.5\ (10^{-9}) \text{ farads.} \\ X_c &= \frac{1}{2\pi f C} = 9340 \text{ ohms per conductor.} \end{aligned}$$

Voltages and Currents.—(a) Having obtained the above data, we will assume that capacity is concentrated at the center of the line and calculate currents and voltages. Diagrammatically, the arrangement is shown in Fig. 223, where conditions represent one line and neutral. $\dot{E}_o$, $\dot{I}_o$, refer to generator quantities; $\dot{E}$, $\dot{I}$, refer to load; r_1, x_1, to line (of one conductor); C, x_c, $\dot{I}_c$, E_c, to the condenser. As we may choose our initial line among these vectors it is most convenient to assume load voltage as having

this direction because it is the starting point of our calculations and is known in value.

Hence we have

$\dot{E} = e$	$E. = 34700 = \text{initial line}.$
....	$P.F. = 0.9.$
....	$\dot{I} = 53.5(0.90 + j\sqrt{1-0.9^2})$
	$= 48.2 + j23.3.$
....	$r_1 - jx_1 = 65.5 - j17.2.$
$\dot{E}_c = e + \frac{1}{2}\dot{I}\,Z_1$	$\dot{E}_c = 34700 + \frac{1}{2}(65.5 - j17.2)$ $(48.2 + j23.3).$ 7

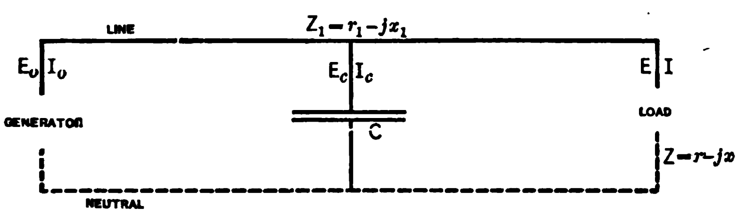

FIG. 223.—Problem A, line calculation, first approximation.

....	$= 36480 + j348.$
$\dot{I}_c = \dot{E}_c / jx_c$	$\dot{I}_c = (36480 + j348) \div j9340.$
....	$= 0.0378 - j3.91.$
$\dot{I}_o = \dot{I} + \dot{I}_c$	$\dot{I}_o = 48.24 + j19.39.$
$\dot{E}_o = \dot{E}_c + \frac{1}{2}\dot{I}_o Z_1$	$\dot{E}_o = (36480 + j348) + \frac{1}{2}(48.24 +$ $j19.39)(65.5 - j17.2).$
....	$= 38227 + j788.$
$Z_o = \text{Total Impedance}$	$Z_o = (38227 + j788) \div (48.24 +$ $j19.39).$
$= \dot{E}_o / \dot{I}_o$	$= 688 - j263.$

Continuing the calculation and deriving the numerical value of each one of the quantities

$e = 34700$ volts.
$i = 53.5$ amperes.
$z = 649$ ohms.
$P.F.\text{load} = 0.90.$
$z_1 = 67.7$ ohms.
$e_c = 36480$ volts.
$i_c = 3.91$ amperes.

$i_o = 51.9$ amperes.
$e_o = 38227$ volts.
$z_o = 737$ ohms for line and load.
$P.F.$, line and load, $= 0.936$.
$e_o\sqrt{3} = 66220$ volts, line-to-line at generator.

(b) In order to reach a closer approximation, it will be necessary to assume a different disposition of the capacity. A better refinement is secured if the total capacity is broken up into three

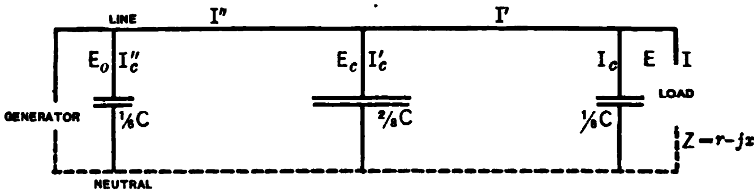

FIG. 224.—Problem A, line calculation, second approximation.

parts and distributed, one sixth at each end of the line and two-thirds at the center of the line. These conditions are indicated in Fig. 224 where the symbols are as before for load and generator, but new quantities are as follows:

$\dot{I}_c$ = condenser current across receiver end of line.
$\dot{I}'$ = line current on receiver side of center.
$\dot{I}'_c$ = condenser current across center of line.
$\dot{I}''$ = line current on generator side of center.
$\dot{I}''_c$ = condenser current across generator end of line.

The reactance of each condenser is derived from the total capacity reactance, being inversely proportional to the capacities. For $\frac{1}{6}\,C$, reactance $= 6x_c$; for $\frac{2}{3}\,C$, reactance $= \frac{3}{2}x_c$.

. . . .	$x_c = 9340.$
. . . .	$6x_c = 56040.$
. . . .	$\frac{3}{2}x_c = 14010.$
$\dot{E} = e$	$E = e = 34700.$
. . . .	$P.F. = 0.90.$
. . . .	$\dot{I} = 48.2 + j23.3.$
$Z_1 = r_1 - jx_1$	$r_1 - jx_1 = 65.5 - j17.2.$
$\dot{I}_c = \dot{E}/j6x_c$	$\dot{I}_c = -j0.6.$

$\dot{I}' = \dot{I} + \dot{I}_c$		$\dot{I}'$	$= 48.2 + j22.7.$
$\dot{E}_c = \dot{E} + \frac{1}{2}\dot{I}'\dot{Z}_1$		$\dot{E}_c$	$= 36480 + j330.$
$\dot{I}'_c = \dot{E}_c / j\frac{3}{2}x_c$		$\dot{I}'_c$	$= 0.024 - j2.6.$
$\dot{I}'' = \dot{I}' + \dot{I}'_c$		$\dot{I}''$	$= 48.22 + j20.1.$
$\dot{E}_o = \dot{E}_c + \frac{1}{2}\dot{I}''\dot{Z}_1$		$\dot{E}_o$	$= 38230 + j575.$
$\dot{I}''_c = \dot{E}_o / j6x_c$		$\dot{I}''_c$	$= 0.01 - j0.7.$
$\dot{I}_o = \dot{I}'' + \dot{I}''_c$		$\dot{I}_o$	$= 48.23 + j19.4.$
$\dot{Z}_o = \dot{E}_o / \dot{I}_o$		$\dot{Z}_o$	$= 688 - j265.$

From these vectors we derive absolute values:

$e = 34700$ volts.
$i = 53.5$ amperes.
$z = 649$ ohms.
$P.F.$ load $= 0.90.$
$z_1 = 67.7$ ohms.
$i_c = 0.6$ amperes.
$i' = 53.2$ amperes.
$e_c = 36480$ volts.
$i'_c = 2.6$ amperes.
$i'' = 52.2$ amperes.
$i''_c = 0.7$ amperes.
$e_o = 38230$ volts.
$i_o = 51.9$ amperes.
$z_o = 737$ ohms.
$P'_o = 1852$ kilowatts per leg.
$P_o = 5556$ kilowatts total.
$P.F.$ line and load $= 0.934.$
$e_o\sqrt{3} = 66220$ volts, line-to-line at generator.
$i_c + i'_c + i''_c = 3.9$ amperes, total charging current.

By comparing these two sets of results, it is seen that they are practically identical throughout. In this case, it is evident that the first approximation would have been all that is necessary.

(c) From Chapter VIII we have

$$\dot{E}_o = \dot{E}\left(1 + \frac{Z_1 Y}{2}\right) + Z_1 \dot{I}$$

$$\dot{I}_o = \dot{I}\left(1 + \frac{Z_1 Y}{2}\right) + Y\dot{E}_o$$

In this problem, our symbols have the values shown below,

$$E = 34700$$
$$\dot{I} = 48.2 + j23.3$$
$$\dot{Z}_1 = 65.5 - j17.2$$
$$Y = \frac{1}{j9340} = -j0.000107$$

$$\therefore \dot{E}_0 = 38224 + j576 \qquad e_0 = 38225 \text{ volts.}$$
$$\dot{I}_0 = 48.24 + j19.39 \qquad i_0 = 52. \text{ amperes.}$$
$$\dot{I}_c = -0.04 - j3.9 \qquad i_c = 3.9 \text{ amperes.}$$

Or, by not neglecting the term $\dot{Z}_1 Y/6$, we obtain practically the same expressions.

This method is to be preferred to any of the other approximations for, upon the whole, it is simpler and more accurate. In this problem, the inaccuracy is not great with any of the methods employed. But in the later problem, it will be seen that the single-condenser method would probably be too far off to be acceptable and the approximation by series is much simpler than the three-condenser method and should be adopted.

Regulation.—Line regulation is the percentage rise in potential at the receiver end of the line when full non-inductive load is thrown off. We may desire to know what the regulation is at any other specified power factor, but, unless the power factor is stated, it is supposed to be unity. In calculating the line regulation at *P.F.* $=0.90$, we may proceed as we have in the previous calculations except that E is not known and is to be determined, while E_0 is known. The capacity may be distributed in three parts, or it may be considered as concentrated at the receiver end of the line. Again, we may estimate it from voltage values we have already calculated as the load voltage, 34700 volts, and the generator voltage which gives this receiver voltage, namely, 38230 volts. This assumes that, with no load, receiver voltage rises to generator voltage, which may give a value too high in one case or too low in another case. In fact, due to line capacity, the potential at the receiver end may exceed that of the generator.

(a) This simplest method gives in the problem A

$$\text{Line regulation} = \frac{38230 - 34700}{34700} = 0.1017$$
$$= 10.17 \text{ per cent.}$$

(b) In order to show the process of obtaining a closer approximation by this laborious process we will assume the capacity as distributed as in Fig. 224.

....	$6x_c$	$=56040$ ohms.
....	$\frac{3}{2}x_c$	$=14010$ ohms.
....	e_o	$=38230$ volts.
....	Z_1	$=65.5-j17.2.$
$E=e$	e	$=?$
$\dot{I}_c=\dot{E}/j6x_c$	$\dot{I}_c$	$=-j17.82e\,(10^{-6}).$
$\dot{I}'=\dot{I}_c$	$\dot{I}^1$	$=-j17.82e\,(10^{-6}).$
$\dot{E}_c=\dot{E}+\frac{1}{2}\dot{I}'Z_1$	$\dot{E}_c$	$=0.99985e-j0.00058e.$
$\dot{I}'_c=\dot{E}_c/j\frac{3}{2}x_c$	$\dot{I}'_c$	$=-j0.0000714e.$
$\dot{I}''=\dot{I}^1+\dot{I}^1_c$	$\dot{I}''$	$=-j0.0000892e.$
$\dot{E}_o=\dot{E}_c+\frac{1}{2}\dot{I}''Z_1$	$\dot{E}_o$	$=0.99908e-j0.0035e.$
....	e_o	$=0.9991e=38230$ volts.
....	e	$=38260$ volts.

Comparing this value with the value of e_o, it is seen that there is a slight rise in voltage along the line. The regulation now appears as

$$\text{Line regulation}=\frac{38260-34700}{34700}$$
$$=10.25 \text{ per cent.}$$

This method is a fair one in a case with considerable line reactance.

(c) If the capacity is placed at the receiver end of the line the calculation is simplified considerably, but at the expense of accuracy. In this particular problem, it does not matter very much which method is used for this last suggestion gives

$$\text{Line regulation}=\frac{38297-34700}{34700}$$
$$=10.38 \text{ per cent.}$$

It is seen that all of the estimates are close together and hence any one of them would have been quite satisfactory in this case.

(d) Finally, for the values obtained by approximation by the series we have

$$\text{Line regulation} = \frac{38270 - 34700}{34700}$$
$$= 10.29 \text{ per cent.}$$

Since

$$E' = E_0 \left\{ 1 + \frac{Z_1 Y}{2} \right\} - Z_1 I_c$$
$$= 38261 + j698$$
$$e' = 38270$$

Telephone Circuit.—Suppose average height of line from ground is 45 feet measured to lowest conductors of the power circuit.

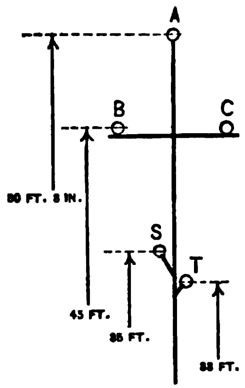

FIG. 225.—Problem A, telephone circuit.

Place telephone wires 2 feet apart, the upper one being 35 feet from ground. These conditions are shown in Fig. 225. They may be stated thus:

Power circuit:

$I \quad = 53.5$ amperes.
$E \quad = 60000$ volts.
Length $= 50$ miles.

Spacings:

$a_s = 15.25$ feet between A and S.
$a_t = 17.25$ feet between A and T.
$b_s = 10$ feet between B and S.
$b_t = 12$ feet between B and T.

$$c_s = 10 \text{ feet between } C \text{ and } S.$$
$$c_t = 12 \text{ feet between } C \text{ and } T.$$

From Chapter VIII the inductance per mile of line A upon the telephone circuit is

$$M_A = 0.741 \log \frac{a_s}{a_t}$$
$$= -0.0403 \text{ millihenrys.}$$
$$M_B = 0.741 \log \frac{b_s}{b_t}$$
$$= -0.0584 \text{ millihenrys.}$$
$$M_C = 0.741 \log \frac{c_s}{c_t}$$
$$= -0.0584 \text{ millihenrys.}$$

Whence, neglecting the negative signs,

$$M = \sqrt{M_A^2 + M_B^2 + M_C^2 - (M_A M_B + M_A M_C + M_B M_C)}$$
$$= +0.02 \text{ millihenrys } = 0.00002 \text{ henrys per mile.}$$
$$e_{50} = 2\pi f M I (50)$$
$$= 8.4 \text{ volts}$$

That is, there will be induced in the telephone circuit an alternating voltage of 8.4 volts at 25 cycles per second.

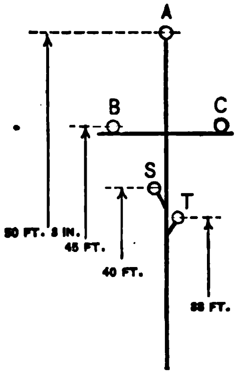

FIG. 226.—Problem A, telephone circuit.

Again, if we place the upper telephone wire only 5 feet below the lower power conductors and recalculate the voltage induced (neglecting diagonal distances and using vertical distances only) we have (Fig. 226)

$a_s \;=10.25$ feet.
$a_t \;=12.25$ feet.
$b_s \;=5.0$ feet.
$b_t \;=7.0$ feet.
$c_s \;=5.0$ feet.
$c_t \;=7.0$ feet.
$M_A=0.741 \log a_s/a_t.$
$\quad=-0.0575$ millihenrys.
$M_B=M_C \;=-0.1079$ millihenrys.
$M \;=-0.05$ millihenrys $=-0.00005$ henrys per mile.
$e_{50}=21$ volts.

The voltage is more than doubled by this decrease in distance.

Each of these calculations indicates that there would have to be numerous transpositions in the telephone circuit in order to eliminate therefrom the flow of current due to this electromagnetically induced voltage, and its consequent noisy effect in the telephone receiver. There remains to be considered the potential at which the telephone circuit as a whole is above the ground potential and the resulting danger to the operator who uses the telephone. This effect is one of electrostatic induction as discussed in Chapter VIII. Referring again to Fig. 225 and stating conditions we have:

$E_o=38230$ volts.
$r \;=0.104$ inch, radius of conductor.
$a \;=603$ inches, A to ground.
$b \;=540$ inches, B to ground.
$c \;=540$ inches, C to ground.
$s \;=420$ inches, S to ground.
$t \;=390$ inches, T to ground.

$$e_a=E_A \frac{\log \dfrac{a+s}{a-s}}{\log \dfrac{2a-r}{r}}$$

$$= 38230 \frac{\log 5.59}{\log 11600}$$

$$= 7020 \text{ volts.}$$

$$e_b = E_B \frac{\log \dfrac{b+s}{b-s}}{\log \dfrac{2b-r}{r}}$$

$$=8600 \text{ volts.}$$

$$e_c = E_c \frac{\log \dfrac{c+s}{c-s}}{\log \dfrac{2c-r}{r}}$$

$$= 8600 \text{ volts.}$$

$$e_s = \sqrt{e_a^2 + e_b^2 + e_c^2 - (e_a e_b + e_a e_c + e_b e_c)}$$

$= 1500$ volts, the potential of S above ground.

Similarly, e_t may be found. These values of potential are, of course, dangerous to the operator.

If the conditions of Fig. 226 are assumed, having only 5 feet between the lower power and the upper telephone wire, the value of potential obtained by a similar calculation is

$$e_s = 2810 \text{ volts.}$$

These values are reached for normal operation of circuits and may be considerably exceeded if abnormal conditions exist, as a grounded telephone return, or a ground return for one phase of the power circuit. The danger depends not only upon the voltage to ground, but also upon the electrostatic capacity of the telephone circuit against ground. The potential may be high even for a very short line, but the charge will depend upon the length of line and will be small for short lines.

One means used to avoid the liability to injury is to install telephone transformers at each end of the line. In other words, the telephone instruments are connected to the line through transformer coils with neutral grounded; the local circuit thus will not participate in the high potential condition of the long lines. This gives absolute protection.

Other methods employ ground wires so placed as to screen the telephone circuit as fully as possible from the power circuit. Probably the best single-ground-wire scheme is to put the two telephone wires upon a cross-arm and run a ground wire midway

between them. The arrangement is indicated in Fig. 227, but, due to field distortion, complete protection is not attainable. With high voltages and long lines, danger still exists. Especially is this true when some abnormal condition arises, as a grounded phase, etc., making it dangerous to use the telephone just when it would be required.

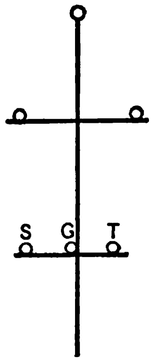

FIG. 227.—Protected telephone circuit.

Problem B.

To deliver 30,000 kilowatts over a 150-mile, three-phase line. Power factor, 0.90.

Choice of Frequency.—Natural frequency of line $=\frac{47000}{150}=313.$

So far as the natural frequency goes, we might use either 60 or 25 cycles. However, if frequency should vary to 62, the fifth harmonic would give the frequency required for resonance. A corresponding variation in generator frequency from 25 cycles per second would affect only the much higher harmonics where danger is considerably lessened. As before, however, the principal feature to consider is line inductance and charging current. It is much to be preferred, then, that the lower frequency be chosen if resonance is not to be expected therefrom. As such trouble is unlikely, we will assume generator frequency,

$$f=25 \text{ cycles per second.}$$

Choice of Voltage.—Allowing as before, about 1000 volts per mile of line, the potential chosen will be about 150,000 volts.

This is above any value now used, but inasmuch as 140,000 volts is under consideration, we may choose that figure and find what characteristics appear in the course of the solution.

Current.

At unity power factor, $I_0 = 124$ amperes.

At power factor 0.90, $I = 137.8$ amperes.

Line Loss.

Let the line loss = about 10 per cent.

Total permissible loss = 3000 kilowatts.

Line loss per leg = 1000 kilowatts.

Approximate power at generator 33000 kilowatts.

Size of conductor:

$i^2 r_1 = 1000$ kilowatts for each line.

$$r_1 = \frac{1000000}{(137.8)^2} = 52.7 \text{ ohms for 150 miles.}$$

A close approximation to this will be secured by the use of No. 000, a 410-mil conductor, of copper. This gives

$$r_1 = 49.3 \text{ ohms for 150 miles.}$$

However, as the current is rather large, we may lower the reactive drop of the line by dividing it into two parallel circuits, as previously shown. This will decrease reactive drop but increase total charging current. It will, at the same time, add to the reliability of the system, especially if the two parallel circuits are placed some distance apart, say 80 to 100 feet.

The conductors required for this arrangement will be two No. 1 wires in parallel. The diameter is 289 mils.

$$r_1' = 99 \text{ ohms per conductor of 150 miles.}$$

$$r_1 = 49.5 \text{ ohms per leg of 150 miles.}$$

The latter arrangement is evidently the better of the two and our continued calculations will be based upon it. It should be noted, however, that the copper wire, No. 1 may be replaced by an aluminium conductor, No. 00, having about the same resistance, and using two in parallel as before. As may be pointed out, this will be especially advantageous for the present problem, in order to avoid heavy corona losses. While one place is satisfactory for the installation of copper conductors, another place may give serious line losses, when the same design of line is used and this

loss may, perhaps, be avoided by using the aluminium with its correspondingly larger diameter. By reference to Chapter XIII, it will be seen under the discussion of corona that the radius of the copper wire chosen for the present problem is too small for the voltage used and the spacing assumed. In fact, it would probably be advantageous to use No. 000 aluminium cable or larger. For our present illustration, however, we shall continue the calculations upon the basis of the small copper wire.

Spacing.—It will be advisable to separate the conductors by a distance of 11 feet and we will consider them as placed at the vertices of an equilateral triangle.

Inductance and Inductive Reactance.

$$L_{mi}=0.0805+0.741\log\frac{d}{r},\text{ where }\frac{d}{r}=\frac{132}{0.145}=910.$$

$$=2.17\text{ millihenrys}$$

$$L_{150}=315.7\text{ millihenrys}=0.3157\text{ henrys.}$$

$$x'_L=2\pi(25)(0.3157)=49.6\text{ ohms per conductor.}$$

$$x_L=24.8\text{ ohms per leg (of two conductors in parallel).}$$

Capacity and Capacity Reactance.

$$C_{mi}=\frac{0.03878}{\log\frac{d}{r}}=0.0131\text{ microfarad}$$

$$C_{150}=1.965\text{ microfarads}$$

$$2\pi fC=3.09\ (10^{-4})$$

$$x'_c=3240\text{ ohms per conductor.}$$

$$x_c=1620\text{ ohms per leg.}$$

Voltages and Currents.

(a) Figure 224 shows the conditions of each *line-to-neutral* where the values used will represent *leg-to-neutral* conditions. Hence, the quantities calculated are for one leg, consisting of two conductors in parallel.

....	$6x_c$	$=9720$ ohms.
....	$\frac{3}{2}x_c$	$=2430$ ohms.
....	i	$=137.8$ amperes.
$E=e$	E	$=80900$.
....	$P.F.$	$=0.90$.
....	I	$=124+j60$.

Z_1	$=r_1-jx_1$	Z_1	$=49.5-j24.8.$
I_c	$=E/j6x_c$	I_c	$=-j8.32.$
$\dot{I}'$	$=\dot{I}+I_c$	$\dot{I}'$	$=124+j51.7.$
$\dot{E}_c$	$=\dot{E}+\frac{1}{2}\dot{I}'Z_1$	$\dot{E}_c$	$=84610-j258.$
$\dot{I}'_c$	$=\dot{E}_c/j\frac{3}{2}\,x_c$	$\dot{I}'_c$	$=-0.105-j34.8.$
$\dot{I}''$	$=\dot{I}'+\dot{I}'_c$	$\dot{I}''$	$=123.9+j16.9.$
$\dot{E}_o$	$=\dot{E}_c+\frac{1}{2}\dot{I}''Z_1$	$\dot{E}_o$	$=87470-j4.$
$\dot{I}''_c$	$=\dot{E}_o/j6x_c$	$\dot{I}''_c$	$=-j9.$
$\dot{I}_o$	$=\dot{I}''+\dot{I}''_c$	$\dot{I}_o$	$=123.9+j7.9.$
. . . .		$\dot{Z}_o$	$=686-j43.8.$

Whence, in numerical values

e	$=80900$ volts.	i''	$=125.1$ amperes.
i	$=137.8$ amperes.	i''_c	$=9$ amperes.
z	$=588$ ohms.	e_o	$=87470$ volts.
$P.F.$	at load $=0.90.$	i_o	$=124.1$ amperes.
z_1	$=55.4$ ohms.	z_o	$=701$ ohms.
i_c	$=8.32$ amperes.	$P.F.$	at generator $=0.998.$
i^1	$=134.2$ amperes.	P'_o	$=10800$ kilowatts per leg.
e_c	$=84610$ volts.	P_o	$=32400$ kilowatts total.
i'_c	$=34.8$ amperes.	$i_c+i'_c+i''_c$	$=52.1$ amperes.

(b) By the approximation by series we have

$$E = 80900.$$
$$\dot{I} = 124+j60.$$
$$\dot{Z}_1 = 49.5-j24.8.$$
$$Y = 1/j1620 = -j0.000617.$$

Whence

$$\dot{E}_o = \dot{E}\left\{1+\frac{Z_1Y}{2}\right\}+Z_1\dot{I}.$$
$$= 87880-j1345.$$
$$\dot{I}_o = \dot{I}\left\{1+\frac{Z_1Y}{2}\right\}+Y\dot{E}.$$
$$= 123.9+j8.7.$$
$$\dot{I}_c = -0.1-j51.3.$$

This gives, for numerical values,

$$e_o = 87890 \text{ volts.}$$
$$i_o = 124.2 \text{ amperes.}$$
$$i_c = 51.3 \text{ amperes.}$$

Regulation.

(a) Calculated by assuming that when load is thrown off the receiver voltage rises to generator voltage, we have

$$\text{Line regulation} = \frac{87040 - 80900}{80900} = 0.076.$$
$$= 7.6 \text{ per cent.}$$

(b) However, if we use the same distribution of capacity in calculating no load voltages as we have in obtaining load conditions, Fig. 224 is again the scheme, except that load is zero.

....	$\dot{I} = 0.$
....	$e_o = 87040.$
....	$Z_1 = 49.5 - j24.8.$
$\dot{E} = e$	$e = ?$
$\dot{I}_c = \dot{I}' = \dot{E}/j6x_c$	$\dot{I}' = -j1.029e(10^{-4}).$
$\dot{E}_c = \dot{E} + \frac{1}{2}\dot{I}'Z_1$	$\dot{E}_c = 0.99745e - j0.00509e.$
$\dot{I}'_c = \dot{E}_c/j\frac{8}{2}x_c$	$\dot{I}'_c = -j0.00041e.$
$\dot{I}'' = \dot{I}'_c + \dot{I}'$	$\dot{I}'' = -j0.000513e.$
$\dot{E}_o = \dot{E}_c + \frac{1}{2}\dot{I}''Z_1$	$\dot{E}_o = 0.9909e - j0.020e.$
....	$e_o = 0.9909e = 87040 \text{ volts.}$
....	$e = 87800 \text{ volts.}$

$$\text{Line regulation} = \frac{87800 - 80900}{80900} = 0.0853$$
$$= 8.53 \text{ per cent.}$$

(c) With the assumed condition that the whole capacity is concentrated at the receiver end of the line, the regulation would become

$$\text{Line regulation} = \frac{88600 - 80900}{80900} = 0.0951$$
$$= 9.51 \text{ per cent.}$$

(d) Regulation by series approximation

$$\dot{E} = \dot{E}_o \left\{ 1 + \frac{Z_1 Y}{2} \right\} - Z_1 \dot{I}_e$$

$$= 88450 - j\ 130$$

$$= 88450$$

$$\text{Line regulation} = \frac{88450 - 80900}{80900}$$

$$= 9.32 \text{ per cent.}$$

In this problem, the calculated values of regulation differ more widely than do those obtained in Problem *A*.

It is thus seen that it becomes preferable to use the fourth calculation, (d), in order to secure the best results.

Telephone Circuit.

The height of lowest power conductors will be taken as 60 feet above ground. If the telephone lines are strung 10 feet and 12

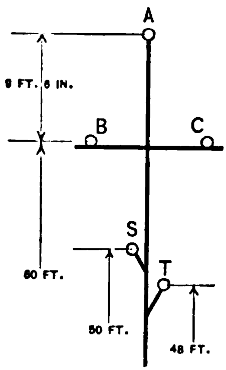

FIG. 228. - Problem B, telephone circuit.

feet lower, the conditions shown in Fig. 228 may be summarized as follows:

$a_s = 19.5$ feet.
$a_t = 21.5$ feet.
$b_s = c_s = 10$ feet.
$b_t = c_t = 12$ feet.
$I = 137.8$ amperes.
Length of line equals 150 miles.

Whence

$$M_A = -0.03055 \text{ millihenrys.}$$
$$M_B = M_c = -0.0584 \text{ millihenrys.}$$
$$M = -0.0279 \text{ millihenrys} = 0.0000279 \text{ henrys.}$$
$$e_{150} = 90.6 \text{ volts.}$$

Lowering the telephone lines 10 feet from the above position, giving distances,

$$a_s = 29.5 \text{ feet.}$$
$$a_t = 31.5 \text{ feet.}$$
$$b_s = c_s = 20 \text{ feet.}$$
$$b_t = c_t = 22 \text{ feet.}$$

will reduce the value of M to 0.00937 millihenrys.

$$e_{150} = 30.4 \text{ volts.}$$

This is a very material reduction but we cannot permit such disturbances as would still result in the circuit and the telephone wires must have frequent transposition points.

With the conditions of Fig. 228 the potential of telephone line S, above ground, is found as before in Problem A.

$$E_A = 87040 \text{ volts.}$$
$$\text{Rad. of conductor} = 0.145 \text{ inches.}$$
$$a = 834 \text{ inches.}$$
$$b = 720 \text{ inches.}$$
$$c = 720 \text{ inches.}$$
$$s = 600 \text{ inches.}$$
$$t = 576 \text{ inches.}$$

Whence

$$e_a = 16870 \text{ volts.}$$
$$e_b = e_c = 26120 \text{ volts.}$$
$$\therefore e_s = 9120 \text{ volts.}$$

If the telephone circuit is lowered 10 feet, however, the net result is to give:

$$e_s = 3000 \text{ volts.}$$

These values of potential above ground potential are very much higher than were calculated for the other problem. Moreover, the line capacity will be much more because of increased length and, hence, the danger to operators is greater. It will be advisable, therefore, as before to install telephone transformers at

Table XXXI.—Summary of Line Calculations.

	Problem A.	Problem B.
Generator		
Kilowatts	5000	32400
Voltage line to line	66300	150800
Voltage to neutral	38230	87040
Current	51.9	124.1
Power factor	0.934	0.998
Frequency	25	25
Receiver		
Kilowatts	5556	30000
Voltage, line to line	60000	140000
Voltage to neutral	34700	80900
Current	53.5	137.8
Power factor	0.90	0.90
Lines		
Length	50 miles	150 miles
Number of lines	1	2
Spacing of conductors	6 feet	11 feet
Altitude of lower conductor	45 feet	60 feet
Size of conductor	No. 4. =0.208 in. diam.	No. 1. =0.289 in. diam.
Material of conductor	Copper	Copper
Resistance per conductor	65.47	99
Resistance per leg	——	49.5
Coefficient self induction =L	109.3 mh.	315.7 mh.
Capacity =C	0.6825 mf.	1.965 mf.
Inductive reactance per conductor	17.2	49.6
Inductive reactance per leg	——	24.8
Capacity reactance per conductor	9340	3240
Capacity reactance per leg	——	1620
Actual line loss	556 kw.	556 kw.
Line loss in per cent.	10%	7.4%
Line regulation	10.25%	8.53%
Capacity current	3.9	52.1
Natural frequency	940	313
Telephone		
Distance below power lines	10 feet	20 feet
Electromagnetically induced voltage	8.4 volts	30.4 volts
Electrostatic potential above ground	1500 volts	3000 volts

each end of the line and at each intermediate station or to protect the line by ground wire. In the long line installation, the latter will probably be preferable, inasmuch as numerous intermediate stations will need to be installed for the sake of patrolmen, even if no side branches to the transmission line occur or installations are served.

With a well protected telephone line, there should be no danger from working on the line or from using instruments connected to the line at any point along the right of way. In order to do this, two leads may be run down the tower, one from each line, to a telephone jack. The lineman or patrolman is furnished with a portable telephone instrument with its leads terminating in a plug to fit the jack. Inserting the plug in the jack will, therefore, put the transmitter and receiver across the telephone line ready for use, and this may be done at any tower. The expense of installing telephone stations at frequent intervals is, thus, very considerably reduced.

The results derived in these problems may be compared in Table XXXI.

Conductor Sag and Length.—When a perfectly flexible cord or wire of uniform weight per unit length is suspended between two points of support, the curve assumed is called the catenary. The solution of this curve is not simple. Moreover, conditions of uniformity of weight, flexibility, etc., are not attained. Hence in the solution of this problem the catenary is rarely used. Without serious error, the curve may be assumed to be a parabola. With this curve, we will assume for our line:

t = horizontal tension, in pounds.
s = span, in feet.
d = deflection, in feet.
w = weight of conductor in pounds per foot.
l = length of conductor in feet.

Then,—

$$t = \frac{s^2 w}{8d},$$

$$l = s + \frac{8d^2}{3s},$$

or

$$d = \frac{s^2 w}{8t},$$

$$l = s\left(1 + \frac{1}{24} \cdot \frac{s^2 w^2}{t^2}\right).$$

Assume a copper wire, No. 000 B. & S. gage. It has a cross-section of 0.132 square inch. If 20000 pounds per square inch be allowed, the pull upon the conductor, with a factor of safety of 4, will be 660 pounds. For a span of 200 feet we have:

$$l = 200\left[1 + \frac{1}{24} \cdot \frac{(200)^2(0.508)^2}{660^2}\right]$$
$$= 200.2 \text{ feet.}$$
$$d = \frac{(200)^2(0.508)}{8(660)}$$
$$= 3.85 \text{ feet.}$$

Similarly, for tension of 660 pounds:

s	100.	200.	300.	400.	500.	700.	1000.
l	100.03	200.2	300.7	401.6	503.1	708.	1025.
d	0.96	3.85	8.67	15.4	24.1	47.1	96.

When spans vary in length along the line, it is best to make the horizontal tension the same on each side of any tower. This can be done, within limits, and the tower is then loaded as a column,

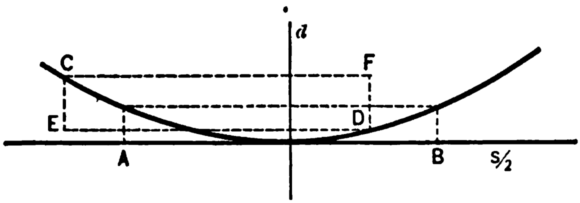

Fig. 229.—Span curves.

if, for the moment we may neglect side strain due to change of direction, wind, etc. The sag, d, is increased with increase of span according to the table just shown. If, then, one long span is plotted for some given value of horizontal tension as shown in Fig. 229 any span having the same tension, conductor, etc., will coincide with a portion of the given curve. If the two supports are at the same *elevation* (not necessarily upon towers of same

height) the portion of the curve used will be its central section, as AB. If the line is descending a declivity, the points of support are not level with each other and the span is displaced from the center of the plotted graph to such a point that the proper difference in tower elevations is secured, as CD. Here, the difference in elevation equals CE or FD, while the span is CF.

Successive spans may be represented, therefore, by the solid portions of the parabolic curves shown in Fig. 230, where the total parabola is the same curve in each case.[1] Towers are

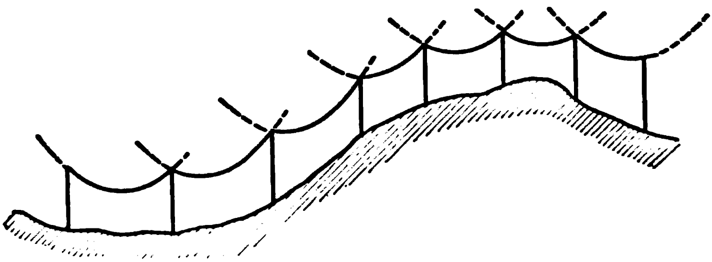

FIG. 230.—Transmission line spans with balanced horizontal tension at poles.

represented by vertical lines at each point of support. The whole figure is greatly exaggerated for the sake of drawing attention to this particular relation of spans. The total tension of a conductor at a point is the resultant of the horizontal component, discussed above, and the vertical component consisting of the weight of the conductor, taken from the lowest point of deflection of the line to the point in question. That is, at A, the total tension, T, of the conductor is equal to the vector sum of the horizontal component and the vertical component equal to the weight of the conductor from O to A.

As this total tension must lie in the direction of the conductor, which is in equilibrium, the relations exist:

$$T=\sqrt{t^2+v^2},$$

where v equals vertical component as before discussed and,

$$\frac{v}{t}=\tan\theta,$$

where θ is the angle that a line tangent to the conductor would

[1] A change of temperature from the standard assumed and the consequent expansion of spans will introduce distortion of curves where the points of support are not at equal altitudes. This representation is, therefore, only a close approximation.

make with the horizontal. But, as the curve is expressed in terms of d and s as variables, the tan θ is the first differential of d in respect to s.

$$\frac{\delta d}{\delta s}=\frac{v}{t}=\frac{sw}{4t},$$

$$T=t\sqrt{1+\frac{s^2w^2}{16t^2}},$$

$$=\sqrt{t^2+\frac{s^2w^2}{16}}.$$

In the case of a span where the supports are at different levels, as CD, the value of the vertical component must still be measured from the low point O to either C or D, as the case may be. The total tension at C will, therefore, differ from that at D. Likewise, the total tension in opposite directions at any one tower need not be equal, although the horizontal components are equal. In this case one span will supply to the tower a greater portion of its vertical load than will the other span.

To the weight of the conductor there must occasionally be added the weight of attached ice and, while exceptional thickness of ice coat may be expected in some localities and under unusual circumstances, ordinary conditions seldom give more severe strains than will correspond to a coating of 1/2 to 3/4 inch. There are cases reported where this is exceeded by factors of four or five, and it must be remembered that the weight of ice increases almost proportionally to the square of the increase of the radius. In many such cases, this liability to interruption is simply recognized as a risk to be added to those already taken by the company, it being considered that effective measures to eliminate the trouble become too expensive.

The most severe conditions imposed upon the line would be a combination of minimum temperature, maximum ice coat and maximum wind. The wind pressure is quite problematical. It adds a horizontal component to the weight strain and, without ice, will rarely add more than 25 per cent. to the total pull for conductors of diameter 1/2 inch or more.

It will be noted that the effect of wind is more severe the smaller the conductor, because the total wind pressure varies as the longitudinal section of the conductor or projected area which

varies as the diameter, while the strength varies as the cross-section or the square of the diameter.

Taking, as a fair extreme, the figure of 15 pounds per square foot of projected area for the total value of the wind pressure and also assuming that this pressure occurs at right angles to the line and horizontally, the strain upon a copper conductor, due to weight and atmospheric pressure, becomes, in pounds per foot of conductor,

$$P=\sqrt{9.12\,d^4+1.563\,d^2}.$$

Reducing this to percentage of weight, and thus expressing the transverse stress in such a way that the effect of wind pressure is recognized as an increase in percentage above 100 per cent,

$$p=\sqrt{1+\frac{0.171}{d^2}},$$

where p is the percentage total stress, d is the diameter measured

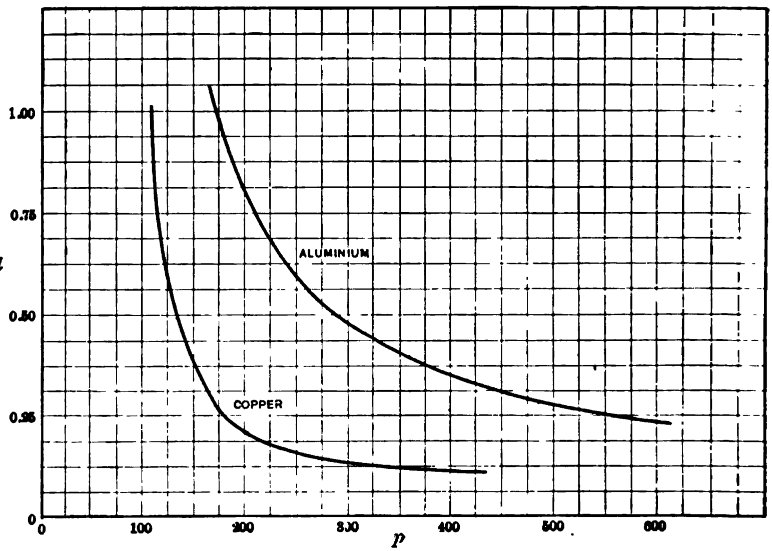

FIG. 231.—Wind pressure curves.

in inches and $p-1$ equals the percentage increase in pressure due to the wind.

Calculated from this equation the relative pressure sustained by wires of different diameters is shown by the curve in Fig. 231.

From this curve it will be seen that destructive effects of wind storms will be more serious with small wires, telephone and telegraph lines, while large power conductors run less risk of interruption of service.

A second curve is shown for aluminium, the equation of which is

$$p_1=\sqrt{1+\frac{1.87}{d^2}}.$$

The conditions represented by this curve are the same as the one previously discussed, except that the conductor is aluminium instead of copper. The conclusion reached by a comparison of the two curves very decidedly precludes the use of aluminium for small conductors if they are to be exposed to wind. The same relative values for aluminium and copper would hold in the case of sleet.

The side pressure thus introduced adds vectorially to the weight of conductor. It is wholly sustained, however, by the poles or towers, and adds directly to the wind pressure upon such towers. In calculating the stress upon towers it is well to place the unit pressure per square foot at about twice the figure used for the conductor because a great deal of the tower presents a flat mesh surface to the wind. Normal conditions may be taken then with 30 pounds per square foot of projected area as a basis for calculation. By projected area in this case is meant the projection of the tower considered as a solid structure bounded by plane faces.

CHAPTER XI.

DISTRIBUTION.

When power has been transmitted to a certain locality after having been developed as electrical power either from the source of fuel or water power, there remains still the problem of distributing it to each consumption point. It is seldom that the whole block of power is used at one point. This condition might be met with where a company owns and operates its own power plant and its load is concentrated in a manufacturing plant. Even here, local distribution is necessary. With an extensive public service corporation, however, the problem is quite different and involves a much wider range of methods and of machinery.

A railway system is fed, normally, from several different points called *substations*. These substations receive power electrically and after having regenerated it in the particular form used by the railway, passes it out to the feeder system, to be absorbed by the load units. A large or widely distributed lighting system may have the same general features, the details being worked out quite differently, probably.

One of the first things to be determined in planning a distributing system is the number of such substations needed. This depends, primarily, upon three things, the distribution of the load, the voltage of the receivers and the load factor of the individual load units.

To a considerable extent, the matter of voltage depends upon the choice made between alternating current and direct current. Where the load is carried upon alternating current, the distribution voltage may be comparatively high, as is preferable. Transformers installed locally will reduce the voltage to the proper figure for the receiving circuit, be it a lighting circuit, or a power circuit. As an example, the power may be generated at a hydraulic plant at 13200 volts, stepped up to 40000 volts, transmitted over some distance to a city which is to use it for lighting. It cannot be carried throughout the city at this high

potential. Nevertheless, it is uneconomical to reduce it to a potential of 220 volts (three-wire system) and so distribute it. Suppose the city to cover an area included within a radius of about 2 miles. In such a case, the power mains would probably be run from one substation at 2300 volts by aerial lines. Branches from these mains will then supply local transformers placed upon poles or within doors, reducing the pressure to 220 volts as demanded by the load. These outside transformers would be small and numerous, frequently as low as 2 or 3 kilowatts and supplying a group of houses in the immediate vicinage. Sizes up to about 7.5 kilowatts would occur for lighting load in the heavier districts but where power is needed for elevators, motor loads, etc., the local installation may be of any size to take proper care of the demand.

If, upon the other hand, the district supplied is much larger or is made up of two cities upon opposite sides of a river and is not laid out in a fairly compact unit, we may have conditions which preclude the use of 40000 volts connecting two distribution centers. The main transmission line may lead to a point near the edge of town or, perhaps, to one of the substations. The links lacking must be supplied at a lower potential than 40000 volts, but it is uneconomical to run low-voltage mains (2300 volts) from such great distances. An aerial line should be run at the maximum potential for which permission may be secured. Or underground construction may be resorted to and cable systems installed. Here, voltages are used as high as 20000 volts. With substations of this nature, the installations are large and few in number.

When direct current is supplied to the load, economical distribution radii are much reduced. The load carried may be railway, lighting or power but in each case the voltage will be low, 220 to 750 volts, and line loss heavy. Generation, if power is transmitted any great distance, will be alternating current and numerous substations will permit of extended distribution of power in smaller blocks in close proximity to the point of utilization, before reduction of voltage. At the substations, then, voltage is reduced, alternating current is changed to direct current and the mains are supplied. It is impossible, however, to carry this increase in number of stations to anything like the extreme

point of one station or source of direct-current supply for each one of the small transformers upon the alternating-current system of distribution, because each direct-current unit will require attention and protection. In short, alternating current permits of high-voltage distribution and a limited number of substations, while direct current necessitates lower voltages and more numerous stations.

As regards the distribution of the load itself, the power company seldom has much control over these features, at least where they are serving the public. Customers may be solicited in certain localities more vigorously than in others, but, to a considerable extent, the demand for power is a growth which can be influenced only by careful and extended planning. Development is very frequently beyond the scope of the service corporation, when it comes to originating calls for factory loads or to building up residential sections. Where, however, the plant supplied is a private one, it must be laid out with careful regard for the necessity of economical supply. This should never be lost sight of and such influence as may be exerted to benefit the general conditions should not be neglected.

Individual load factors are of lesser import to the engineer in charge of the layout as they are apt to be more changeable than the demand. However, a poor load factor, one indicating light demand throughout the greater part of the day and a comparatively heavy demand for a short time, cannot be allowed to influence too greatly the location of stations or of heavy feeders. A good method of determining both the number of substations needed and their location is to map, to scale, the location of all loads and the magnitude of the demand. This may be the average demand or the maximum demand, in which latter case, the load factor characteristics should be tabulated if attainable.

Assuming certain average distances for substation service, or radii covered by each, a trial number of stations may be established and the load upon each calculated. Alterations in the arrangement may then be made and new estimates prepared. A comparison of these various results should include consideration of estimated cost of installation and of operation, as well as the matter of proper voltage regulation. Important items are such as cost of

Real estate,
Buildings,
Equipment,
Distributing mains,
Feeders to maintain proper voltage regulation,
Attendance,
Operation,
Maintenance.

A very accurate determination of such data as the cost of equipment, maintenance, etc., will involve the consideration of proper installation of units as regards both type and size, and a discussion of these will be undertaken later.

A railway load may have either of two distinctly different characteristics. It may be a local system, with a well distributed network of lines, or it may serve a long narrow strip, perhaps the main line of an interurban. All possible gradations from one to the other, naturally, may be expected. The same restrictions hold, however, as to the effect of choice between alternating current and direct current, but by far the greatest number of installations are with direct current. The necessity for so many substations upon a direct-current trunk line has given rise to the introduction of alternating-current railway service and to the use of 1200 volts direct current.

Whatever the service, the power supply generally needs regeneration at the substations before it is usable at the load. This gives rise to the use of a large variety of machines covering changes that may be required from alternating current to alternating current, from direct current to direct current, from alternating current to direct current and from direct current to alternating current, the use of regulators, etc.

Regeneration.

Transformers.—Constant potential transformers are built with a definite ratio of number of turns primary to number of turns secondary corresponding to the change desired in voltage of the alternating-current circuits. Fundamentally, it is one of the simplest machines possible, consisting, as it does, of primary and secondary windings insulated from each other and assembled

to link with the same iron core with no moving parts. Its successful operation is a matter of insulation and magnetism. The added refinements to its operation, however, as in efficiency, regulation, heating, etc., bring about restrictions in the design which cause serious study. Voltages obtainable have kept pace with the demands made by service and any potential required may be secured, with the exception of extreme values desired for testing and experimental purposes. In these directions, it is a simple matter to ask for more than the manufacturer will undertake to supply, but, where the machine is to be used upon commercial work, the problem of utilization injects an element of caution into requests.

Commercial transmission voltages have reached the value of 110,000 volts, and engineers are contemplating 140,000 volts to 165,000 volts. In such cases the practice is to build three-phase transformers. The Great Western Power Company in California has thus installed six three-phase 10,000-kilowatt transformers for supplying its 100,000-volt line.

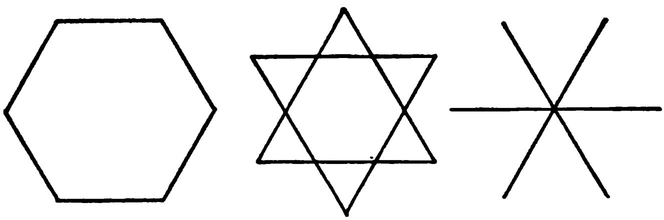

FIG. 232.—Transformation from three-phase to six-phase.

Upon the other hand, distribution of power constitutes the process of breaking up into lesser parts the bulk of power and supplying numerous small consumers scattered over a wide area. Transformers for this use may be large or small, single-phase or polyphase, etc., as occasion demands.

There are occasions when it becomes necessary to change from one polyphase system to another. The change from three-phase to six-phase (or *vice versa*) is the most frequent of these and is an exceedingly simple process. It is accomplished by connecting the transformer primary three-phase Y or △ and by connecting the three secondary coils at their centers, giving a six-point star

arrangement; or by using six secondary coils, two in each transformer, the double-delta arrangement will give six terminals equidistant electrically. Similarly, six coils may be connected up in a closed figure—a hexagon—presenting like characteristics. These three arrangements of secondaries are shown in Fig. 232. The necessity for this usage occurs in supplying six-ring converters from three-phase circuits. In fact, this is practically the only place where the demand is made, but it is met so frequently that it is a very important arrangement.

Another revision of phase conditions occurs in the change from three-phase to two-phase. While not as common as the

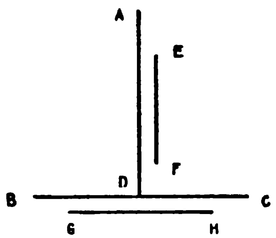

FIG. 233.—Scott transformer connections.

three-phase to six-phase transformation, it still is used enough to become important. It involves the use of two single-phase transformers, connected T. The three-phase circuit supplies power at the three T terminals and the two-phase circuits are taken off, independent or interconnected, from the individual secondaries. With the diagrammatic arrangement shown in Fig. 233, if transformer *BC* is wound for a ratio of 10 to 1, transformer *AD* must be wound for 8.66 to 1. The secondaries *GH* and *EF* are each of the same voltage, giving balanced voltage conditions. As before remarked, the two-phase circuits fed by the secondaries may be independent of each other, they may be connected in L for three-wire distribution or they may be connected at their neutrals giving a four-point star. The neutral to the three-phase side may be brought out if a two-thirds tap is supplied to the winding *AD*. This transformation is used where a two-phase load, as motor, etc., is to be carried upon a three-phase system. It is known as the "Scott connection."

Frequently, the two transformers are built as duplicates of each other, in which case the excess primary winding of machine AD would extend, diagrammatically, below the point D. This makes D an 86.6 per cent. tap in the primary coil and the neutral tap comes from the 57.8 per cent. point. As a midpoint tap is required for the machine BC, there are necessary in each one three taps, namely, at the points 50, 57.8, and 86.6 per cent.

Transformer ratios may be made of any values. The simplicity of the step in manufacture of changing the ratio of the numbers of turns has lead to the confusion of establishing a great multiplicity of ratios. Wherever possible, the ratios should be standardized and made even integers up to and including 5 : 1, then 10 : 1 or multiples thereof. It is possible in such cases to interchange transformers more readily in case of accident or to make other use of a transformer which has been replaced, etc. These ratios are sometimes as high as 50 : 1, although 10 : 1 and 20 : 1 are to be preferred from the standpoint of economy of construction of a high-voltage transformer. That is, if a machine is to supply 110,000 volts, it can be built more cheaply if its low-voltage coils are to receive 11,000 volts than it mav if the pressure is to be 2200 volts.

Such ratios will fit in very well with the generator-transmission line end of the plan because generators may be had at voltages up to 15,000, without excessive cost. But at the distribution point of a very high voltage line the higher ratios must be used because the individual consumer will not have apparatus of suitable size to pay to build it for high voltages. In case double transformation occurs, as already mentioned, lower values of ratio are available.

When ratios become as low as 2 : 1 or less (fractional ratios being quite common), if there is no necessity for insulation of primary circuit from secondary circuit, there is frequently a saving accomplished by the use of the *auto-transformer*. The conditions are shown in the two sketches in Fig. 234 where (*a*) shows the primary and secondary coils as independent. The ratio assumed is 1.5 : 1 and the currents as 20 amperes primary and 30 amperes secondary. As primary and secondary currents are opposed to each other (nearly 180° apart) a combination of the two circuits as in (*b*) will cancel part of the current in certain

portions of the circuit. The new conditions show currents in transformer leads are as before but the winding has 20 amperes in the end turns of the primary not included in secondary and 10 amperes in the combined primary-secondary section. Assuming that the copper used is adjusted to the current density, the saving in the coils only would figure, in this case, as 66.66 per cent. If it is not considered economical to use two sizes of copper conductor because of labor expense, etc., the saving will be only 50 per cent. Theoretically, there will always be a saving in

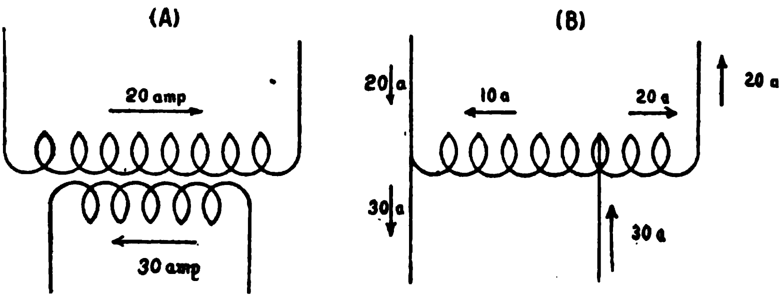

FIG. 234.—Development of auto-transformer.

copper cost whatever the transformer ratio, if the windings are combined and each portion is adjusted to the proper current density. But this saving decreases as the ratio becomes large and other points in design soon overbalance it, so that, generally speaking, auto-transformers are not used for ratios above 2 or 3 to 1. Separate windings are placed upon cores quite frequently where even a 1 : 1 ratio is desired, in order to insulate the secondary circuit from the primary circuit. Probably the most frequent use made of the auto-transformer is in starting devices for alternating-current motors where full voltage cannot be thrown on at standstill.

The *regulation* of a transformer is defined as the ratio of the rise in secondary terminal voltage from rated non-inductive load to no load (at constant primary impressed terminal voltage) to the secondary terminal voltage at rated load (Stdz. Rules A. I. E. E.). With a decrease in load from normal to zero, there is a decrease in secondary current, a decrease in flux leakage between primary and secondary and a corresponding rise in

secondary terminal voltage. This is, then, a source of instability in the ratio of terminal voltages as load changes, and, hence, is of prime importance in the consideration of voltage regulation of a local system requiring constant potential for most satisfactory operation. The regulation allowed depends altogether upon

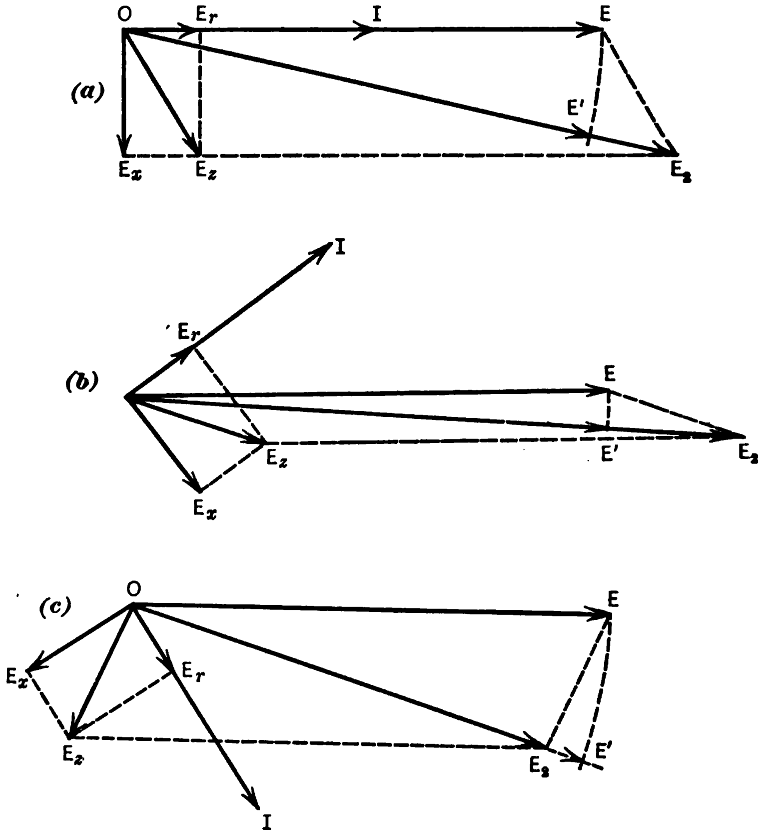

FIG. 235.—Transformer regulation.

the nature of the load to be supplied. It is common to specify values of about 1.4 per cent. for non-inductive loads. This change in secondary terminal voltage is, of course, due to the impedance drop of the windings. It is made up of resistance drop, inductive reactive drop and capacity reactive drop. The

inductance, however, overbalances the capacity, so the resultant impedance is resistance plus inductive reactance. It follows directly from this, that, not only will the value of power factor affect the regulation, but so also will it be differently affected by equal power factors occurring under leading load or lagging load conditions. This may be best seen by reference to Fig. 235, (*a*), (*b*), (*c*). The condition of non-inductive load is represented (with exaggerated values) in (*a*), inductive load in (*b*) and capacity load in (*c*). All three figures are lettered similarly and are covered by the following discussion:

I = current, value and phase.
E_r = voltage to overcome resistance drop of transformer.
E_x = voltage to overcome reactance drop of transformer.
E_z = voltage to overcome impedance drop of transformer.
E = rated secondary terminal voltage.
E_2 = voltage generated in secondary coils.
E' = E(numerically).
$E'E_2$ = rise in voltage when load is thrown off.

If the line OE is laid off as 100 per cent., the length of $E'E_2$ becomes the percentage of regulation. It is quite evident, from a comparison of the three diagrams, that an inductive load, because of its lagging current, injures regulation while capacity load, because of its leading current, benefits regulation. In the extreme and exaggerated cases shown the regulation with capacity load has become negative, i. e., a *decrease* in voltage occurs when load is thrown off and *increase* occurs with increase of load. This is quite analogous to regulation of a transmission line as discussed in Chapter X.

Transformer efficiencies are easily kept at high values. There are none of the sources of loss present analogous to friction, windage, etc., of the moving machine. The losses consist of iron losses and copper losses. In general these two parts are about alike in amount, although certain ends may be reached by proportioning them differently.

The copper losses vary as the load changes, the variation being proportional to the square of the current. Iron losses vary only slightly when load changes. If, then, a transformer is to be connected to circuit continuously, the core loss occurs continu-

ously regardless of load conditions. It is, therefore, a greater percentage of load with light load than it is with heavy load and, consequently, a heavy core loss tends to depress the efficiency curve abnormally for light loads. The condition is illustrated in Fig. 236. The machine would be unsuited to installation upon a circuit with poor load factor or where it would have to remain permanently connected to primary mains during no load. Its all-day efficiency would be poor.

If the iron loss is light and full-load copper loss heavy, the curve will be tipped in the opposite direction from normal.

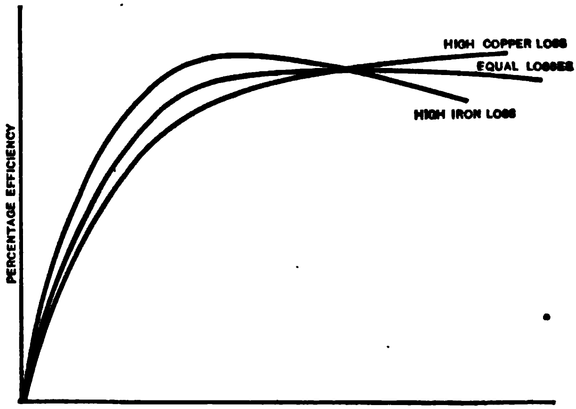

Fig. 236.—Transformer efficiency curves.

With decrease in load the main source of loss becomes less and less prominent, resulting in a rise in efficiency toward no load, and in a rapid falling off above normal rating. This curve is also shown in the figure and contrasted with those for heavy iron losses and for equal losses.

Typical efficiencies as obtained may be seen from Table XXXII.

Depending upon the characteristics due to variation in loss division, efficiencies are affected by the voltage of the transformers. For example, the efficiency of a low-voltage transformer will be low owing to heavy currents. If iron losses are kept down in order to have fair efficiency at low load, the curve is still further depressed. High-voltage machines tend to increase iron losses and decrease copper losses. These tendencies, of

course, can be overcome by the use of more copper and more iron respectively, and this is where cost price is affected by efficiency requirements.

Table XXXII.—Typical Transformer Efficiencies.

Kilowatts.	Full load.	Half load.
1	92.0	90.0
2	94.0	92.0
5	96.0	94.0
10	97.0	95.0
50	97.4	95.5
100	97.8	95.7
500	98.0	95.9
1000	98.2	96.0
3000	98.3	96.4
5000	98.4	97.0
10000	98.5	98.0

The losses of power in transformer operation evidence themselves in the form of production of heat and rise in temperature of coils and core. This causes certain difficulties. The rise in temperature of the copper increases the resistance of the windings and the loss still farther increases. The occurrence of high temperatures will lower the effective value of the insulating materials used in coil construction. Excessive temperatures will permanently injure the insulation if continued for any length of time. This heat may originate in either coil or core and be conveyed to the insulation in process of its radiation.

In the core, especially in the older irons used, high temperatures were apt to increase permanently the core loss by injuring the quality of the iron. In later irons, this may not be so serious and much higher temperatures could be permitted in the iron if it were possible to prevent this heat from reaching the coils and their insulation. It would seem that this might be accomplished fairly easily with some methods of cooling. The fact remains, however, that coil and core are so intimately connected that with

certain types of machines it will prove to be impossible to take any great advantage of this permitted temperature rise.

In cooling transformers, different processes are devised using convection, conduction and combinations of these with assistance in the removal of the medium used to absorb the heat.

The simplest of these, unassisted radiation, is seldom used except for very small units. In general, it is possible to make some provision to help in the process of cooling but occasional instances arise when it seems impracticable. An instance occurs to the author where a 25-kilowatt single-phase unit was asked for to be placed inside an underground 6-inch tube and shut off from all possibilities of air currents, etc. In a case of this sort, high efficiency is of prime importance because it indicates limited energy radiation in the form of heat.

Departure from this construction may be in either of two directions. The machine may be designed in such a way that air when once heated may cause a natural draft through ducts provided therefor, or the unit may be immersed in a substance with higher specific heat than air and provided with greater radiation surface.

Natural draft has a very limited range and is not seen in machines except of the smallest sizes. The other scheme, however, is a very successful one. By immersing the transformer in oil and so proportioning the containing tank that the surface is increased to such a value that the loss radiated in watts per square inch of surface is suitable to the conditions, a practicable design may be made for transformers of several hundred kilowatts. Transformers installed for outdoor service, especially lighting service, are of this type. An instance of such usage is illustrated in Fig. 237 representing the outdoor installation of a three-phase 6600-volt transformer used upon a power circuit of the Grand Rapids and Muskegon Power Company's lines.

The air-cooled machine is developed into a commercial possibility by forcing air through its cooling ducts. This is known as the *air blast transformer*. It is built in the shell type, i. e., with the iron surrounding the greater part of the coils. The core is provided with ducts spaced about 2.5 inches apart. Air chambers are provided in the station, over which the transformers are set, blowers being used to maintain pressure in the chambers.

The pressure varies from 1/2 to 3/4 pound per square inch, depending upon the length of air passage to be followed. The percentage of total power required to furnish this air when blower sets are used may be as low as 0.25 per cent. for banks of about 1000 kilowatts to 0.10 per cent. for banks of 10,000 kilowatts. Air pressure should be uniform at all machines in order to insure good working conditions. It is usual, with banks of large or medium capacity, to install duplicate blowers in order to take care of the cooling in case of disability of one blower. They are set, in such cases, one fan at each end of the air chamber, but as close to the transformers as possible. Air chambers should be free from projections or sharp turns and should have smooth uniform surface. They should be tight, clean, and so situated that they may secure a plentiful supply of clean, dry, fresh air. This must be without long restricted feed passage, for such a source of supply means increased power demand upon the blower or reduced pressure in the pit beneath the transformers. As a rough approximation, the amount of air required may be estimated as 150 cubic feet per minute for each kilowatt loss of transformer core and coils. The amount used may be checked as regards its sufficiency, by reading temperatures of the ingoing and outgoing atmosphere. A rise of about 20° C. is generally considered satisfactory, although this may be exceeded with cold air supply but should not be permitted with warm air supply.

FIG. 237.—Outdoor installation of three-phase 6600-volt transformer by Grand Rapids and Muskegon Power Company.

In size and voltage, the air blast transformer does not reach either extreme. It is a rather expensive machine to build, and hence is not used in small sizes nor is it common for very low

voltages. Large sizes make it necessary to provide long air passages which again introduce undesirable conditions for cooling. High voltages similarly bring into consideration larger bodies of insulating material, less efficient cooling, and limits are set by liability of corona. There are several advantages which make the air blast transformer valuable and account for its very general use. It is much simpler to operate than water-cooled machines; it is easily inspected; its ventilation and cooling system may be relied upon to do extra duty when overload is demanded of the transformer; it is cleanly and does not detract from the appearance of a station.

When very large sizes or high voltages are demanded, a further development of the oil-cooled machine is used,—namely, the *water-cooled type*. No attempt is made to use the cooling effect of increased tank surface, hence, the tank is not fluted or corrugated. Within the tank are placed tubular coils to carry cooling water. These coils are of wrought iron, copper or brass, depending upon the chemical properties of the cooling water, the first mentioned being much cheaper than the others and entirely satisfactory upon almost all occasions. Only when there are chemicals in solution which will attack the iron does it become necessary to replace it by the more expensive construction. The pressure generally maintained is much below the value for which copper tubing will be guaranteed while the iron piping is some five or six times stronger than the copper.

The cooling coils are placed in the upper part of the tank where the rising warm oil strikes them. After threading its way through the passages among the turns and giving up its heat, the oil descends along the sides of the tank. It then moves inward toward the center, enters the ducts and openings in the transformer core and between the coils and rises, absorbing heat again, to be cooled as before. Successful design necessitates a careful study of oil flow and the position of ducts and other openings relative to each other.

The oil used in any type of transformer for insulation and as a cooling medium should have certain properties, including good insulating quality, high flashing point, not too great viscosity, purity, etc.

A heavy mineral oil is found to be satisfactory. Kerosene is

suitable in many respects, but its high inflammability is a very serious defect from the standpoint here assumed. If an oil is too thick, it will not circulate well through the ducts. Impurities are subject to deterioration and may reduce the dielectric strength because of their own presence or because of the presence of the products formed. The most troublesome impurity and the most dangerous one is water. The oil will not absorb water, as does alcohol, but owing to alternate heating and cooling condensation and precipitation of water may occur. When once mixed with oil, the water will sink toward the bottom of the tank. It becomes more or less finely divided and in its highly divided state is suspended in the body of the oil. The decrease in dielectric strength with the increase in oil content is exceedingly rapid at first (i. e., from 0 per cent. up to 0.02 per cent. moisture). In fact, the presence of as little as 0.2 per cent. water in the oil decreases its value as a dielectric over 50 per cent. This indicates that great care must be taken to keep the oil dry in shipment and in assembling or operating the machines.

To test for the presence of moisture in oil, a sample drawn from the lower part of the tank after the oil has remained undisturbed for some 24 hours, may be put into a small, dry open vessel. If a red hot wire be thrust into the oil, the presence of moisture will be evidenced by a succession of sharp hissing explosions. The test may be made by the use of copper sulphate. The ordinary hydrous crystal should be heated and dried until it loses its water of crystallization and incidentally its color. The anhydrous sulphate is then dropped into a vessel containing the oil sample and the whole thoroughly shaken. If moisture is present, the color of the sulphate will change again to its normal hue, dark blue. The only very delicate test, however, is the disruptive strength in a needle gap.

In order to remove the moisture, a considerable portion will remain in the containing vessel by allowing it to stand for a day or more without disturbing and then drawing off the oil from the top. The oil thus removed may be completely dried by dehydrating chemicals. Another process, which is found to give excellent results, is to force the oil under heavy pressure through blotting paper which retains the moisture but allows the oil to pass.

Heat may be applied to evaporate the water, but this is done, preferably, in connection with a vacuum method. Other methods used are (1) heating the oil, by transformer coils and external heat, and (2) passing warm dry air through the oil. Neither of these processes is absolute, although they are quite effective. The oil should stand test potentials of 25,000 to 40,000 volts between needle points placed 0.2 inch apart.

Before the transformer is put into service, the coils and dielectrics should be dried as well as the oil, if there has been the least opportunity for moisture to accumulate. The coils may be dried at the same time as the oil in some of the above methods. A short-circuited run at normal current will gradually drive out moisture from coils. But with heavy insulation and partitions this is not completely effective. Hence the high-voltage machines must be dried by blowing dry hot air through them for several days. After installation, samples of oil should be taken frequently and tests made in order to certify to the presence of good operating conditions and no gradual collection of moisture again. This testing becomes less frequent after a few months.

High potential should never be placed upon coils before they have been dried after a disassembled shipment.

A recent type of transformer, used in large sizes, cools the oil by pumping it out of the transformer tank into coils running through cooling water. The type is still "oil-cooled" but no water enters the tank to absorb the heat.

The choice among these different types—oil-cooled, air-blast and water-cooled—leads to a consideration of numerous points.

The oil-cooled transformer is practicable and can be constructed economically up to about 1500 kilowatts, the air-blast type covers the range from 100 to about 5000 kilowatts, while the water-cooled may be seen in all sizes from 100 kilowatts to the largest built—some 14,000 kilowatts.

The oil-cooled and water-cooled are upon a par in this respect because the insulation is the same in each case. The highest voltages are obtained thus. The air-cooled is not seen for potentials above about 33,000 volts.

For a given small output, the oil-cooled occupy the least room. As the total amount of power increases, however, this advantage would be lessened because this type would have to be installed

in comparatively small and numerous units. Water-cooled have the advantage here if cooling water is obtainable by means of piping only, as at a hydraulic plant. When water must be pumped, the room taken is considerably increased, and this again must be increased if the water has to be used again after cooling by towers, storage tanks or other devices. This may occur in connection with steam plants running condensing, making use of the condensing plant for the double purpose.

The air-blast type will always require room for a commodious air pit and for the blowers. This may be more or less than that needed by the water-cooled, depending upon the number of accessories required by the latter.

In the simple form, the water-cooled transformer may be built at a slightly lower figure than the oil-cooled for the same rating, except in small machines where the latter has decided advantage. The air-blast machine will be somewhat more expensive than either of the others.

All transformers must be kept dry and clean. Oil must be tested occasionally for moisture content. Beyond this and due care of terminals, the oil-cooled machine requires little attention.

The water-cooling system demands attention to valves, water supply, water temperatures, etc. This is liable to be more than the requirements of the blower system where electric motors are easily cared for.

The choice between single-phase and polyphase machines is generally determined in the case of polyphase circuits by the number of units to be installed. A polyphase machine is cheaper than a similarly rated set of single-phase machines. When a large number of transformers is needed, the reserve units are of the same type, necessarily, as the operating units, and the use of polyphase machines with polyphase reserves is warranted. For the loaded machines three-phase units are cheaper than single-phase units would be and so also for the spare machines. However, with one or two polyphase circuits required, polyphase transformers would be cheap, but polyphase spares would be expensive. If single-phase units are installed any spare transformer may be utilized to replace any phase of the injured bank, and as the injury occurs frequently in only one phase, this substitution still leaves the other uninjured members in useful

condition. With no spares, the injured machine must be detached from the circuits for repairs, leaving an open delta—with delta-connected single-phase machines—to carry 58 per cent. of normal load until the difficulty is righted. A polyphase machine would necessarily leave the load uncared for during the repairs.

Again, numerous single transformers will mean rather complicated connections, with many leads and many terminals. This is a necessary feature accompanying flexibility.

When transformers are to be operated in parallel, their impedances must be inversely proportional to the loads they are to take. If, then, they are of equal ratings, their impedances should be alike. It is upon this account that the constants for old transformers are needed by manufacturers who are filling an order for new machines to be operated in multiple therewith.

Transformer reactances vary considerably, and upon non-inductive load it does not matter very much because regulation is not very seriously affected. With inductive load it becomes a matter of considerable consequence, where regulation is to be close. Upon transmission lines where load is fairly constant, the change in voltage supply with varying load is not of great importance and heavier reactance may be allowed. Moreover, if a transformer is built with a reactance as great as 8 or 9 per cent., there is much less danger of serious mishaps to the machine and its supply circuits, in case of short-circuits, etc., than there would be with a reactance of only 2 per cent.

In arranging transformer connections, there are two things which should be taken into consideration. One of these is the reliability of service. This has already been mentioned in the discussion of phase connections. When a $\triangle$ connected transformer temporarily loses one phase, it can still run open delta and carry 58 per cent. of normal load. If that phase is a single-phase transformer it is to be disconnected from circuit and removed. If it is one of the phases of a three-phase machine it must be disconnected and short-circuited, primary and secondary. A Y-connected circuit does not have this feature. Another point to consider in connection with abnormal conditions is the possibility of failure of certain phases, leaving a highly reactive transformer circuit in series with the heavy capacity of a trans-

mission line. When such conditions arise, resonance may occur, with still further disaster. It must be remembered that a transformer coil with its corresponding coil open on the other side of the machine (i. e., primary and secondary coils) becomes a reactive coil of high inductance. An illustration of this condition is shown in Fig. 238. The transformer, ABC, may represent either end of the system, generator or receiver. $A'B'C'$ is connected to the transmission line. If one of the local lines is open, as at X, this phase A is unexcited. A' then becomes a reactive

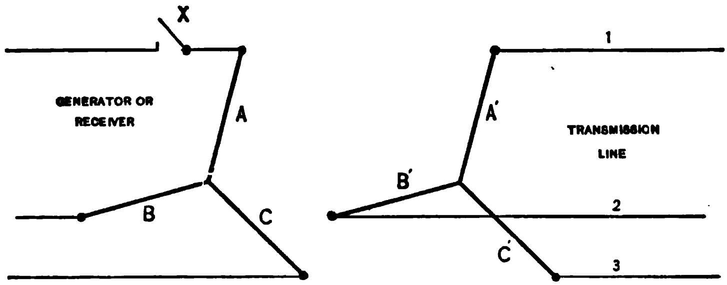

Fig. 238.—Resonance due to irregular transformer connections.

coil in effect. But it is in series with the other elements. Of 1, 2, B' or 1, 3, C', both B' and C' are excited. 1, 2, and 3 each has considerable capacity. This, then, may give resonance conditions, depending upon the relative amounts of these quantities. The severity of the consequences will likewise depend greatly upon the amount of resistance in these circuits.

Constant-current transformers are used principally for series lighting circuits. There are developing numerous electrochemical processes, however, where constant current regulation may be preferable. For instance, in electric furnaces one kind of service may demand constant power regulation, another may need constant current.

Transformers for these purposes may be secured of rather limited sizes and voltages. Owing to the fact that the coils must be adjustable as regards distance in respect to each other, construction generally gives one coil (the high potential) a fixed position, with the other coil movable along the central core. Necessarily, the ratings both in kilowatt capacity and in voltage must be kept comparatively low. Where arc lighting furnishes

the load, the transformer is generally rated in the number of lights it will carry, as 25, 50, 75 or 100 lights. The current at which it is to regulate is also specified, as 6.6, 7.5 amperes, etc.

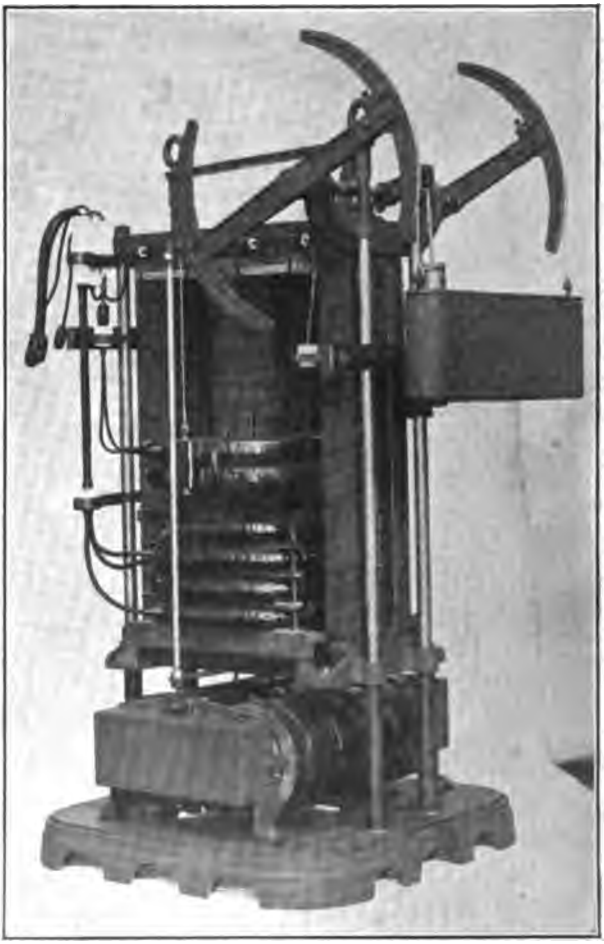

FIG. 239.—Constant-current transformer.

A machine of this type is shown in Fig. 239. It is intended to carry a load of 75 lights with a current of 6.8 amperes, requiring from 6000 volts to 6600 volts,

Owing to the peculiarity of the distribution of iron in such transformers, the power factor at full load (coils together) is quite low, say 0.75 to 0.80. For light load the transformer regulates by separating the coils and increasing the leakage flux. This means a still further decrease in power factor, a typical curve being shown in Fig. 240. There are also shown typical efficiency curves. All of these curves are for arc circuit loads and this materially depresses the power below what it would be for the transformer alone.

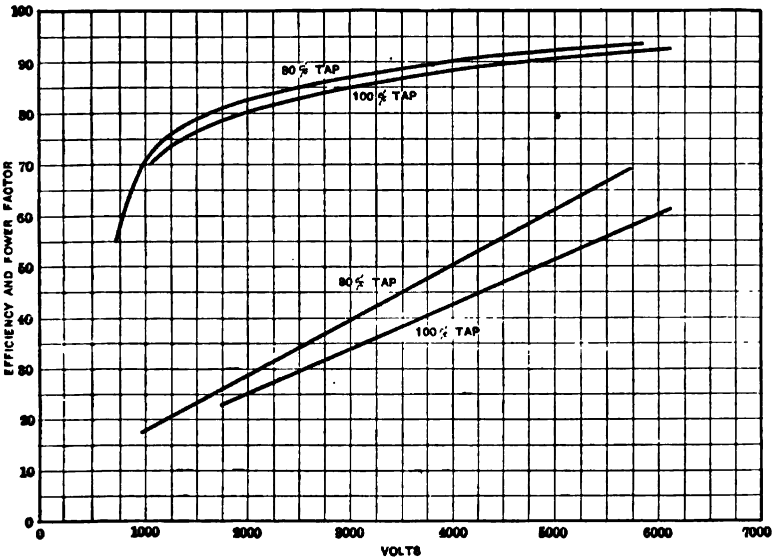

FIG. 240.—Power factor and efficiency of constant current transformer with arc light load.

Frequency changers are commonly built in the form of motor-generator sets. In this type, the number of poles upon the motor bears the same ratio to the number of poles upon the generator as does received frequency to transmitted frequency. The most common change desired is that from 25 cycles per second to 60 cycles per second. The numbers of poles, motor and generator, will vary for different sizes of machines, but the ratio must always hold, motor to generator, of 25 to 60, that is 5 to 12. This means, of course, the use of relative values such as 10 to 24,

20 to 48, 30 to 72, etc., if it is required that the ratio shall be exact. When other systems or circuits do not add complications to the system considered, however, there is no particular reason for requiring this refinement, as a 60-cycle circuit is practically not different from a circuit of 58 1/3 cycles or 62.5 cycles, and these frequencies may be secured from a 25-cycle supply by slight variations from the 5 to 12 ratio.

A set of 10 to 24 poles is the least where the exact ratio can be reached. The kilowatt output may not warrant the expense of building a set with these numbers of poles. In such a case, a 6 to 14 pole set may be used, giving a frequency of 58 1/3 cycles per second.

A second approximation for slightly larger sets or for different conditions may be secured by the use of 8 to 20 poles, giving 62.5 cycles. This value may often be given preference over the 6 to 14 set when induction motors are to be carried as load, because it leaves the induction motor speed at about 60 cycles rather than at a value less than 58 1/3 by the slip.

Again, the jump from 10 to 24 poles to 20 to 48 poles leaves the same consideration of expense to be settled. In this range we find:

12–28 poles giving 58.3 cycles,
14–32 poles giving 57.1 cycles,
16–40 poles giving 62.5 cycles,
18–42 poles giving 58.3 cycles.

The exact ratio of 40 to 60 cycles is quite easily handled, and where single frequency changing sets of this type are used, the process of putting the machines into service is accomplished by the ordinary method of starting synchronous motors, to be described later. When parallel operation of sets is necessary, meaning, by this, the phasing in of motors and the phasing in of generators also, an added complication occurs. The two machines of a set are mechanically bound together by the shaft. Phasing in the motors of different sets may be accomplished by bringing into proper relationship any pole of one with any corresponding pole of the other. In Fig. 241 there are shown, diagrammatically, two frequency changer sets with ratio of poles, 6 to 14. The inner circle in each represents the 6-pole motor,

the outer circle, the 14-pole generator. Suppose all fields to be excited, this being done in such a manner as to make all odd-numbered poles of one (say north) and even-numbered poles of the opposite polarity (south). The motors may then be phased in with, pole 1 of *A* corresponding to 1-*B*, 3-*B*, or 5-*B* (inner circles). The corresponding conditions of generator poles may then be determined by imagining *B* superimposed upon *A*, successively in each of the above mentioned positions. It will readily be seen that a coincidence of 1-*B* with 1-*A* motors will give similar coincidence of 1-*B* and 1-*A* for gen-

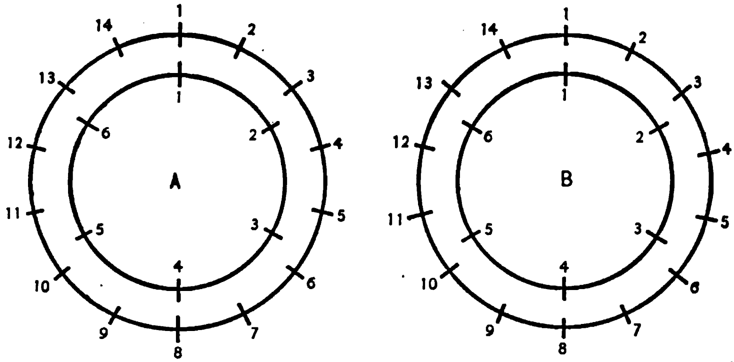

FIG. 241.—Phase relation in frequency changer sets.

erators. If, then, the two motors are thrown together electrically with this relationship, the two generators are ready to connect in parallel also. Suppose, however, that 3-*B* is the *N*-pole which is made to correspond to 1-*A* in the motors. Turning *B* around till the two poles thus correspond, the generator poles will not coincide, *A* and *B*, and the circuits of the two generators may not be connected. A similar condition exists if 5-*B* and 1-*A* are made to correspond to each other, and the generaators cannot be paralleled. The practical way out of this difficulty is to cause one motor to *slip a pole* one or more times until symmetry and correspondence occurs upon both sides. Slipping a pole is accomplished by reversing the field current in the motor, in which case the motor loses speed for an instant and regains synchronism after having lost a pole space by mechanical displacement. This may be repeated and the motor will lose the

same mechanical angle each time, finally giving proper conditions. The process may sometimes be abridged by reversing the field of the generator also. This is the case when mechanical correspondence of generator poles occurs with electrical opposition, meaning a real 180-degree displacement of fields. A reversal of the generator field will then preclude the necessity of several more reversals in the motor.

For example, suppose the machines in the foregoing discussion fall into synchronism with motor poles 3-*B* and 1-*A* corresponding. The generators are out of phase. A reversal of the field of motor *B* brings a 4-*B* and 1-*A* correspondence. Now, generator pole 8-*B* (*S*-polarity) corresponds to generator pole 1-*A* (*N*-polarity) and a single reversal of generator field will permit paralleling. Without this reversal, three more reversals of motor field, with consequent slipping of poles, would be necessary in order to accomplish the same result. An excellent exposition of this subject is made in an article by Mr. J. B. Taylor in the A. I. E. E. Trans. of 1906. Division of load among several such sets or even between two is a matter for very precise adjustments. If two generators, running in parallel, are in phase with each other, their internal constants and their field excitations will determine their load division. When the two alternators are not in phase with each other a cross current will flow between the machines disturbing this balance of load. Hence an inaccurate coupling of motor to generator in one of two sets which are to operate in parallel will leave the two sets without proper load division, because the two motors are fairly near the same phase position or epoch. If, then, the two generators are displaced from the motor epoch by unlike amounts, they are out of phase with each other and the cross currents result. So delicate an adjustment is it that where the sets are to be run in parallel, the generators are mounted on "cradle" bases which permit a shifting of the stationary armature throughout a large enough angle to assure similarity of epochs. The Institute paper above mentioned gives curves showing the division of load for seven sets operating in parallel, having various ratings, 250 and 500 and 1000 kilowatts.

The induction motor presents the possibility of use as a frequency changer also. If secondary is supplied with definite

windings, three-phase, two-phase, etc., the frequency of generation therein corresponds to the slip of the machine, i. e., to what the secondary lacks of maintaining full synchronous speed. By driving secondary at a predetermined speed, any secondary frequency may be obtained over a range from zero to double supplied frequency without going above normal speed for the rotor. This gives the *induction type* of frequency changer.

Commutation and Rectification.—It is very frequently necessary to change from alternating current to direct current, and various methods are used depending upon the nature of the service required. Synchronous rectifiers or commutators, mercury arc rectifiers, electrolytic rectifiers, rotary or synchronous convertors and motor generators, all come under this heading.

The first of these, the synchronous commutator, is of no particular use except in its very successful development in the ordinary direct-current armature. Here, of course, it has universal use and is indispensable. But in its special form, a commutator synchronously driven by a small alternating-current motor and supplied with alternating current to be taken off its direct-current brushes, the operation does not lend itself well to general practice.

The electrolytic rectifier depends upon the "valve action" of certain cells using various electrolytes and electrode pairs of aluminium and carbon, lead, steel, etc. They are uniformly of very low efficiency, of the magnitude of 30 per cent., and are usable only upon very intermittent loads or other places where the cheapness of the device very greatly overbalances the cost of operation with such low efficiencies.

The mercury arc rectifier, however, has been very well developed in the last few years and is being found adaptable to many situations. It may be used upon polyphase or single-phase circuits, the accessories depending upon the number of phases.

In the single-phase application the ratio of voltages may be derived approximately from a consideration of the following relations. One-half the alternating-current supply voltage is across the local circuit consisting of one side of the mercury arc, reactance coils and load. During one half-cycle the side a of the transformer or reactance coil (Fig. 242) supplies the local circuit, while during the next half-cycle the side b carries the

load. As each half-cycle may be considered as active in the direction from the center of the transformer toward its respective ends, the direct-current voltage is the average of this series of half-waves. Then

E = effective alternating-current voltage supplied.

$1/2\ E$ = effective voltage across half transformer.

$\frac{1}{2}\sqrt{2}E$ = maximum voltage across total local circuit.

$\frac{2}{\pi}\cdot\frac{\sqrt{2}}{2}E = 0.45E$ = average, or direct-current voltage of total local circuit.

There is across the arc itself a constant potential drop of 13 volts which must be subtracted from the above values. There is, also,

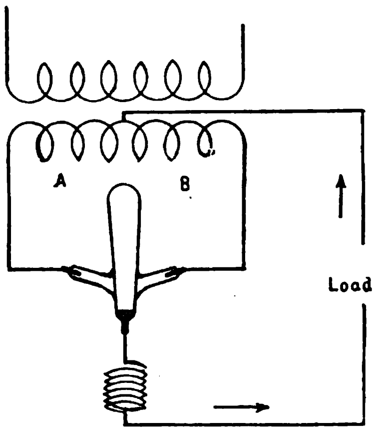

FIG. 242.—Mercury arc rectifier circuits.

a voltage drop across the reactance coils and this must again decrease the actual direct-current load potential. So far as the arc alone is concerned, the direct-current voltage becomes

$$E_o = 0.45E - 13.$$

Hence, if E, the alternating-current supply, is high the ratio E_o: E is greater than it would be for low values, because in order to arrive at the value of E_o, there is subtracted from a constant fractional multiple of E_o a constant value 13 volts, but this

becomes a lesser percentage as the potential increases. In terms of power, the same kind of statement may be made. The voltage drop is a constant across the arc, the *loss* varying as the first power of the current and being *ie.*, or $13i$. The resistance of the arc varies and becomes less with a higher current. The efficiency of the rectification rises, therefore, with rise of potential.

In the above equation for E_0 we have neglected the effect upon the voltage of the overlapping current half-waves during which time the transformer is short-circuited by the arc. In constant-current rectifiers the current, being smaller, requires more overlap of half-waves and the effect is to decrease the voltage about 10 per cent. Moreover, the arcs maintained are longer and have a drop of about 18 volts. Hence, for constant-current conditions we have, approximately,

$$E_o = 0.41E - 18.$$

When used for series arc circuits the rectifier is supplied with constant current and variable potential by the use of the constant-current transformer, already mentioned. Pressures as high as 13,200 volts may be used. At these high voltages special precautions are taken to eliminate static discharges across the tubes.

In using the rectifier for battery charging, low voltages only are necessary, but the current capacity is increased. This soon

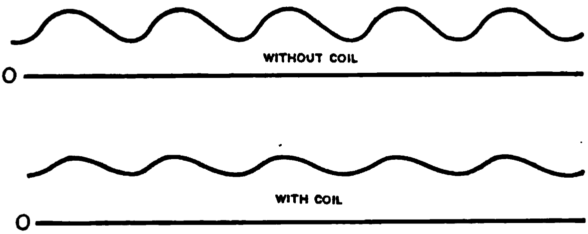

FIG. 243.—Direct-current curves for mercury arc rectifier.

reaches a limit, however, for, as pointed out, while increased potential of the system does not increase the *ie* loss in the arc, an increase of current will augment this product and, consequently, the heating of the apparatus. In order to run at high-current values, it is necessary to cool the rectifier tube. It is somewhat advantageous to turn a fan upon the tube, but a more effective

process is to immerse the tube in oil and cool the oil by water flowing through cooling coils as in transformer tanks.

The current obtained from the mercury arc rectifiers is *direct* but not continuous. In order to smooth out the wave more or less according to the use for which it is intended, a reactance coil is placed in the direct-current circuit. Figure 243 shows the current as rectified but without the tranquilizing effect of a heavy reactance coil and, in contrast thereto, the current obtained when such a coil is placed in the circuit.

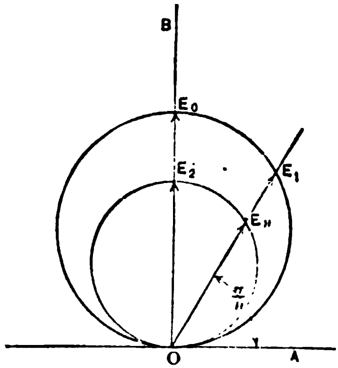

FIG. 244.—Voltage ratios of synchronous converter.

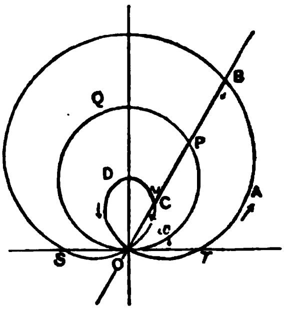

FIG. 245.—Current cycle in synchronous converter armature coil.

Synchronous converters have a greater usage than any other form of converting apparatus. This machine also has the advantage over the rectifiers just described in that it is reversible, it may be used with alternating-current to direct-current conversion or with direct-current to alternating-current conversion. Until the last few years, the voltage ratio alternating current to direct current has been given as a constant for a specified number of phases, although it had been recognized that wave shape would alter this ratio quite perceptibly. A convenient method of determining these ratios for machines of any number of phases is represented in Fig. 244. The diameter OE_o represents the direct-current voltage and is taken as unity. OE_1 is laid off at an angle π/n from the initial line, where n equals the number of rings upon the alternating-current end of the armature. The circle on OE_2 as diameter is drawn with the relation

$$OE_2 = \tfrac{1}{2}\sqrt{2}OE_o.$$

Then we have:

OE_o = direct-current voltage between brushes.
OE_o = maximum alternating-current voltage between *diametrical* rings.
OE_1 = maximum alternating-current voltage between *adjacent* rings.
OE_n = effective alternating-current voltage between *adjacent* rings.
$OE_n : OE_o$ = voltage ratio of converter.

In other words, if OE_o is unity, OE_n represents, to scale, the ratio sought. It is seen from the figure that

$$OE_n = \tfrac{1}{2}\sqrt{2}OE_o \sin \frac{\pi}{n}.$$

Hence

$$E_n = \tfrac{1}{2}\sqrt{2}E_o \sin \frac{\pi}{n},$$

where

E_n = alternating-current voltage.
E_o = direct-current voltage.

The current in the converter coils is a combination of the alternating wave and the direct current. In polar coordinates this gives a circle (the sine wave) plus and minus a constant (the constant current). The resultant curve is a limaçon as shown in Fig. 245. An armature coil displaced from the center of a phase by an angle ω will pass through the cycle shown $OABPCDO$, first in a positive sense, then in a negative sense. The center coil of any phase will give the cycle $SOCDOTS$ where the reversal along the straight line TS corresponds to the instant of commutation as did the line BPC in the other cycle shown. It is evident, therefore, that the current in a coil displaced from the center of a phase is greater than that in the center coil. Moreover, the farther the angular displacement, the greater is the current.

The polar diagram has the property of showing enclosed areas varying as the square of the parameter. The areas enclosed by the two curves *show to scale the comparative heating in the coils* because this heating varies as the square of the current. Coils

having various displacements (0 degrees, 15 degrees, 30 degrees, . . .) are shown in Fig. 246, for a 3-ring machine and for a 6-ring machine. They are drawn to the same scale and the shaded areas show comparative heatings of successive coils. The greatest displacement possible with the 3-ring machine is 60 degrees, while only 30 degrees from the center coil may be reached with a 6-ring machine.

From these diagrams we may conclude that the heat developed in the rotary armature becomes less with an increase of number

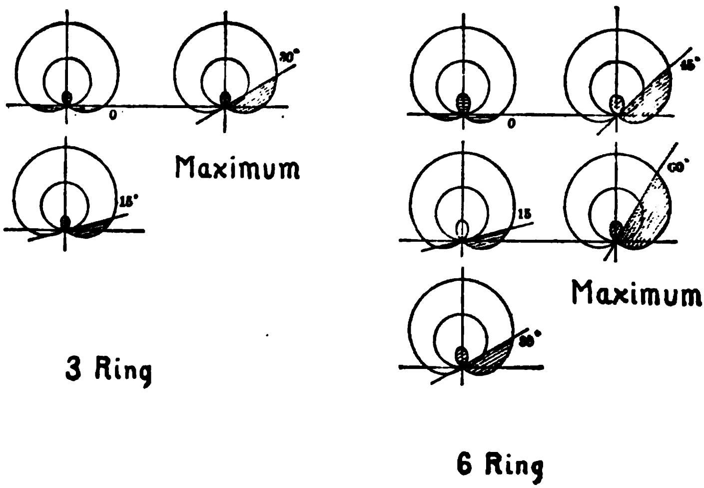

FIG. 246.—Synchronous converter armature heating.

of rings. Furthermore, the production of heat in the armature of the synchronous converter is much more uniformly distributed the greater the number of phases of the machine. Hence, in using three-phase circuits, it is much preferable, with large machines, to use transformer connections giving six-phase secondaries and connecting to six rings upon the converter.

The effect of change of power factor from the value of unity, which has been assumed in the foregoing, is to make the electrical center of the phase fail to coincide with the mechanical central coil. Excessive heating will occur at one end of the phase and reduced heating at the other. (See *Electrical World*, Jan. 21, 1909.)

The synchronous converter is especially useful in converting large bulks of power from one condition to the other. For example, the machine has become a necessity in connection with modern direct-current railway systems. To feed these systems may require alternating-current transmission and distribution with local conversion to direct current. And it is here, especially where the converter has intrenched itself very strongly. It has many of the characteristics of the synchronous motor. One of these properties which frequently makes it useful is the possibility of changing the power factor of its load demand. It must run at synchronism, hence, a change of field current will not alter its speed but will vary its phase conditions. That is, an over-excited field demands from the line a leading component of armature current to counteract this over-excitation and reduce field flux to its normal value; an under-excited field demands a lagging component of armature current to bring the flux up to normal. The convertor, may, therefore, be used in conjunction with induction motors, where some direct-current load is to be carried upon an alternating-current system, more logically than may induction motor-driven direct-current generators. The regular induction motor load will depress the power factor of the system. An induction motor carrying as load a direct-current generator will also tend toward low power factor. But a convertor run with high field current will tend to correct for the lagging current of the induction motors. It is quite possible to have beneficial results from the use of such a machine even when running idle, as will be pointed out later in connection with synchronous motors.

These machines can be built for 2000 kilowatts or more, and, for smaller machines, with voltages of 1200 direct current. For these higher potentials, commutating poles (interpoles) are used. In order to secure 1200 volts, however, it is possible to run two machines in series upon the direct-current side, remembering that the alternating-current rings must be supplied through transformer sets not interconnected, upon the secondary side.

As before implied, within the last few years it has been found practicable to build convertors of variable ratios. One of the schemes for accomplishing this result is based upon the distortion of the voltage cycle represented by a circle (sine wave) in Fig.

244. If by superimposing suitable harmonics upon this wave it is considerably changed in shape, the ratio of E_n to E_o may be altered.

This is illustrated in Fig. 247, where a third harmonic has been added to the fundamental, being in such a position as to increase the direct-current voltage, E_o, and thus *decrease* the ratio, $E_n : E_o$. This same harmonic reversed will give an *increase* in ratio. The mechanical arrangement of the pole piece for this scheme is a division into three parts, the center section being excited independently from the two outer sections.

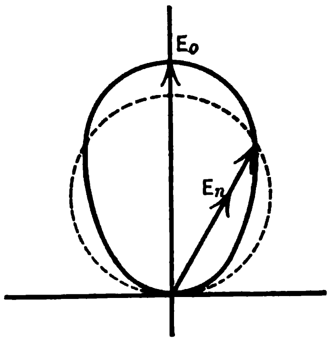

FIG. 247.—Split-pole converter voltage ratios.

The same end may be accomplished by other wave distortion, as, for example, leaving E_o constant but varying the curve in the region of E_1. In this type, the pole is split into two parts, one wide and one narrow, the latter being excited in such a manner that the flux in it is brought down to zero and again brought up to normal value in the opposite direction. In the meantime, an auxiliary winding upon the main pole has kept total flux from the combined pole the same, thus maintaining constant power factor. This effects a shift of flux with greater concentration for zero excitation of the "split" pole, while with "split" pole contra-excited, the direct-current brush will be found to rest upon the commutator at a neutral point of the armature but between two sections of like polarity. The result in wave shape may be such as to leave the wave as a whole practically of

the same shape except in the region of the brush, where a neutral commutation point is provided upon the wave, at what would otherwise be an active region. This makes commutation possible along a chord of the wave (polar coordinates) other than the diameter and will reduce the direct-current voltage, with corresponding rise in ratio.

Normal ratio in a 3-ring machine is about 0.63 with load. With the above variations in construction this may be made as high as 0.75 to 0.80.

Although no demand has caused development along this line there is no insurmountable reason why two such commutation points may not be provided upon the same armature, giving a convertor from one direct-current voltage to another direct-current voltage.

Motor-Generators.—There remains the most flexible combination for conversion of electrical power in the form of the motor-driven generator. With this combination, any relation of voltages may be obtained, within the reach of the individual units themselves. Direct or alternating currents are equally practicable upon either motor or generator. This gives, as an advantage not possessed by the synchronous convertor, the possibility of receiving at a high voltage and using in local load at a low voltage without the intervention of transformers. As an example, suppose a direct-current load is to be carried at 125 volts from 6600-volt alternating-current mains. Induction or synchronous motors may here be called upon to drive 125-volt direct-current generators. Frequency changers are generally voltage convertors at the same time. For flexible relations between two direct-current voltages, this usage is universal.

It is the case, however, that by far the most important work, which the convertors of all types are called upon to do, is to change from medium and high alternating-current voltages to ordinary direct-current voltages. Where this may be accomplished by motor-generators without the use of transformers, synchronous convertors are at somewhat of a disadvantage because they would always require the intervention of transformers. However, we must put the cost of a two-unit set against the cost of transformers and a single-unit machine. Efficiencies may also be of considerable importance and in this

particular the convertor has the advantage. Motor-generator sets ranging from 200 to 2000 kilowatts can probably be obtained at prices from $25.00 per kilowatt to $16.00 per kilowatt. Transformers and convertors covering the same range and combined would cost about $23.00 per kilowatt to $17.00 per kilowatt. These figures will depend upon voltages and frequencies and are so nearly alike that it is probably safer to consider first cost as the same in each case. A necessity for transformers in connection with motor-generators would probably make the comparison favorable to the convertors. The lower the direct-current voltage the more expensive the machines, and with lower frequencies, the variation is in the same direction for transformers but gives decrease in cost for rotaries.

Table XXXIII.—Typical Efficiencies of Various Machines.

Kilowatt capacity.	Motor.		Generator.	Convertor.	Transf.	Motor generator.		Transformer and convertor.
	Syn.	Ind.	D. C.	600 v.	6600 v.	Syn.	Ind.	
25	90.0	89	85.0	92.0	95.0	76.5	75.7	87.5
100	92.0	91	90.0	92.5	97.0	82.8	81.9	89.7
500	94.0	92	91.0	94.0	97.5	85.5	83.7	91.6
1000	94.5	93	91.5	94.0	98.0	86.5	84.7	92.2
2000	96.0	95	92.0	96.0	98.0	88.2	87.5	94.0

As regards efficiencies obtained, the figures in Table XXXIII may be regarded as typical, though they vary with voltages and frequencies and may be considerably bettered for anyone who is willing to pay for a more expensive machine. In general, synchronous motor efficiencies are a little higher than induction motor efficiencies. The generator column refers to direct-current machines and the last three columns give products of individual

efficiencies corresponding to synchronous motor-generator sets, induction motor-generator sets and transformer-convertor sets. Even here, these efficiencies may be bettered in some machines by decreasing the number of bearings, the windage, etc. Convertors, being synchronous machines, are subject to the same advantages and disadvantages as are synchronous motors. The matters of power factor, regulation, hunting, alternating-current starting conditions, etc., will be touched upon under the heading of the latter machine.

The convertor may, however, take advantage of its direct-current features in providing for starting. That is, it may be started from the direct-current end and phased in upon the alternating-current end after coming up to speed.

Load Characteristics.—It is very seldom that any distribution system can be rated absolutely as a lighting system, a power system, etc. Much less can one find a simple heating system. An arc lighting circuit comes as near the simple condition as anything, but in practically all cases the load is characterized by that term covering the predominant demand. Nearly every constant potential lighting system is called upon to supply power for elevators, fans, battery-charging sets, small motors for lathes, planes, saws, sewing machines, etc., etc. With the present development of heating apparatus, this range is rapidly being widened to include cooking utensils of all types, radiators, water heaters and other small apparatus where electricity is used in competition with gas, coal, kerosene and alcohol. The growth of this patronage is of considerable importance to the central station in its influence upon the load factor. "New business" departments fostering this kind of service have generally accomplished very satisfactory results. As a consequence of these conditions, all sorts of load units are assembled in the total load carried by public service corporations. The general features of these various numbers will be discussed, having in mind the character of the service rendered and the effect upon the aggregate system. Similarly, types of machines and devices used upon more specialized systems will be included.

The American Institute of Electrical Engineers gives a classification of electric motors in regard to speed conditions. While these outlines cover both alternating- and direct-current motors,

the latter will be found to give more varied illustrations of the characteristics there mentioned. Quoting from the standardization rules we have:

(a) Constant-speed motors, in which the speed is either constant or does not materially vary, such as synchronous motors, induction motors with small slip and ordinary direct-current shunt motors.

(b) Multispeed motors (two-speed, three-speed, etc.), which can be operated at any one of several distinct speeds, these speeds being practically independent of the load, such as motors with two armature windings.

(c) Adjustable-speed motors, in which the speed can be varied gradually over a considerable range, but when once adjusted, remaining practically unaffected by the load, such as shunt motors designed for a considerable range of field variation.

(d) Varying-speed motors, or motors in which the speed varies with the load, decreasing when the load increases, such as series motors.

The induction motor.—From the standpoint of operation, the small polyphase induction motor is the simplest motor obtainable. This is especially the case if the squirrel-cage rotor is used. Even with variable secondary resistance or starting compensators, simplicity is still a marked characteristic of starting and of operation.

The motor is known as a constant-speed machine because it runs at approximately constant speed with change of load. It is rated at the speed which it would have if running at synchronism and which it cannot attain as a motor because of slip. However, the percentage of fall in speed from synchronism to full load condition is comparatively small, amounting to about 8 to 6 per cent. in very small machines and only 4 to 2 per cent. in large machines. This increases at a slightly greater rate with overload, but in many machines is fairly uniform until a total load of 200 to 300 per cent. or even more is reached. The speed curve then rapidly bends downward and the machine quickly reaches its maximum output at a speed of about 75 to 80 per cent. of synchronous rating. The induction motor, therefore, does not regulate for variable speed but has a definite speed for each definite load. Neither does it run at one constant speed.

Where either of these demands is made—absolutely constant speed or variable speed—this motor is unsuitable.

Variation in frequency of the alternating-current supply has identically the same effect upon this induction motor as in the case of transformers. Because of the relation $x = 2\pi fL$, x varies directly with f. Hence, if voltage is maintained constant, the exciting current of an induction motor (practically the running-light current) will vary inversely with f. This is not quite true because of resistance but is a close approximation. It follows, then, that upon a system of different frequency from the rated frequency of the motor, the voltage should be changed corresponding to the change in frequency.

Variation in voltage (alone) will cause a change in current, but torque, being proportional to the product of flux and current, varies as the *square of the voltage.* A reduction to half-voltage across the terminals of the motor will give a current curve of one-half the normal current curve, but the ordinates of the torque curve will be divided by four. Each curve will retain its individual characteristic shape, of course. The maximum torque will still occur at the same value of speed, say 80 per cent., and current will steadily decrease from the time of starting. Stable running conditions will be reached at a greater slip than with normal voltage.

The induction motor may be built with accessories which give it excellent initial torque, suitable for starting a considerable static load as in the case of line shafting, etc. Where this is not required the machine may start with very small demand upon the line. Depending upon these starting conditions and the size of the unit, there are built several types of induction motors.

The motor with squirrel-cage secondary is the simplest and in small sizes is started by throwing full voltage directly upon the primary. This would hold up to about 5 horse-power. One torque curve and one current curve cover this case. Current is large and falls off to normal. Torque is rather small (i. e. a little greater than normal load torque) and increases to a maximum, decreasing again to normal. This method should not be used in starting any heavy load because of low initial torque and because of heating in case of slow starting and correspondingly

slow diminution of current. Nor should it be used for frequent stopping and starting without time to cool the motor in cases of considerable power demand. Large motors are built of this type but they are not started in this manner because of the effect it would have upon line voltages. They are provided with auto-transformer starting devices by means of which a lower voltage than normal may be employed at first.

As has been pointed out, this reduction in voltage accomplishes a like reduction in current and a second power reduction in torque. This is advantageous in that the current in the motor is reduced and heating is less. Current in the supply line, being received at full voltage, is reduced by the second power or as the square of the voltage reduction, causing a lesser fluctuation in line voltage. Furthermore, the torque is still great enough to bring the motor up to approximately full speed, running light, within a limit permissible without making this acceleration too great and causing unnecessarily large starting stresses. Large induction motors with squirrel-cage secondaries are started, then, upon very low torque curves and are not suitable for setting in motion any mechanical system of large friction of rest.

When the resistance of the secondary of an induction motor is increased, the torque curve is shifted proportionally toward greater slip. The current curve is similarly shifted. Both of these curves pass through the same cycle of values, as before except that these instantaneous values occur at lower speeds. This feature allows for changes in torque at standstill suitable to any condition. In Fig. 248 are shown the torque-slip curve and the current-slip curve (or, in the reverse sense, the speed curves, as they are generally called) giving normal position and successive curves, for increasing secondary resistance. The maximum torque point is shifted to a point beyond standstill (i. e., backward running) so that the motor starts upon the stable side of the torque curve with predetermined torque value. At a suitable speed the shift is made to a lesser resistance and a less displaced torque curve, the process being repeated until all secondary auxiliary resistance is cut out and normal running conditions exist. This scheme allows either a very low torque for starting with a correspondingly low current or a torque of any desirable magnitude up to maximum if such value should be

necessary. It is therefore more flexible than the voltage-control method.

In practice individual resistances are inserted in each definitely wound secondary phase. This resistance, if not too bulky, may

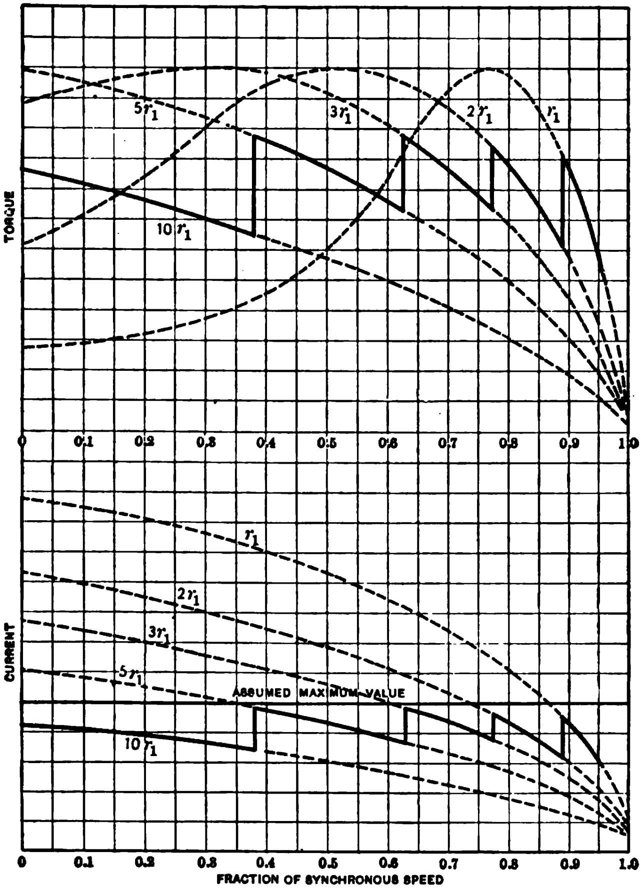

FIG. 248.—Torque-speed and current-speed induction motor curves.

be mounted upon the revolving member. Otherwise, it must be external to the machine, which must allow for its insertion by bringing out each secondary phase to slip rings. In running conditions, the resistances are finally short-circuited at the rings in order to lower the secondary resistance as far as possible.

This makes possible a good running condition and a starting condition adjustable to demand.

By variation in construction, the induction motor is capable of giving two or three definite speeds and is then known as a 2-speed or 3-speed machine. This end is accomplished by winding the stator in such a way that the number of poles may be changed by switches in the armature circuits. A 12-pole machine upon a 60-cycle circuit would give 600 revolutions per minute. By certain changes of switches the winding becomes an 8-pole winding and the speed will now be 900 revolutions per minute. A further change to 6 poles will give 1200 revolutions per minute. This complicates circuits, however, and is rarely carried above 2 or 3 speeds.

Where polyphase circuits are not available, single-phase induction motors of small sizes may be secured. They are used in sizes up to about 50 kilowatts and are generally provided with devices which make them self-starting. Such apparatus may be made up of combinations of reactive coils, condensers and resistances generally spoken of as *phase-splitting devices*. They are generally permanently connected to the motor terminals in such a manner that they may be cut out for normal running. They are assembled in the base of the motor.

Near full load the running curves of single-phase induction motors are much the same as for polyphase except that the efficiency curve is a little lower and droops more quickly for the former machine. The power-factor curve rises a little slower in the single-phase machine because of increased magnetizing current. These differences, however, are not great and quite satisfactory results may be obtained by the use of single-phase motors. They should not be called upon to start more than a very moderate load, however, because the simple single-phase motor has no torque at standstill but must be started by some mechanical means or it must operate polyphase at first. As soon as it is once in motion, the torque curve rises, sweeps up over a maximum value and down to the stable point very much as in the case of polyphase machines.

The synchronous motor is a constant-speed machine differing from the induction motor which is approximately constant speed, in that it runs at the same speed, whatever the load,—namely,

the speed of the rotating flux. The difference comes from the fact that, in the induction motor, slip must occur between primary and secondary in order to generate a secondary voltage, resulting in a secondary current, while in the synchronous motor the secondary current is the supplied field current which is responsible for definite polarity of the magnetic material of the secondary member.

The induction motor takes a heavier load by losing a little speed and increasing the voltage generated in the short-circuited secondary winding. This causes an increase in secondary current and is accompanied by an increase in primary current. The two opposing currents give a combined magnetomotive force which is the source of the actual magnetic field. We have, then, an increased secondary current in a nearly constant field. This gives increased torque, as the latter is always proportional to the product of armature current and that component of the field flux which is in *time phase* therewith but in *space quadrature.*

The synchronous motor will carry a heavier load by falling back slightly in the mechanical position of the revolving field in respect to the rotating flux of the armature. This changes the vector relation between the electromotive force of the armature and the counter electromotive force generated therein by the field. The resultant vector of electromotive force increases in length and this will force a heavier current through the armature. As in the other case, the result is an increased torque.

This angular lag or *sag* of the motor pole and its flux behind the flux due to armature current will increase, up to a certain value,—namely, the impedance angle of the armature ($tan^{-1}x/r$). Beyond this value the motor stops because of overload. This point of breakdown does not occur at the same load if the field excitation is varied. In fact, a considerably greater value of power is obtainable before breakdown with a little over-excitation than would be with light field current. This is not due to a greater flux with increased field excitation, because when a synchronous motor field current is changed, the result is to change the power factor by bringing into the armature a current component leading or lagging in respect to the power circuit. This out-of-phase component magnetizes an under-excited field (lagging current) and demagnetizes an over-excited field (leading

current), but in each case the effect is to leave the flux at its normal value—that corresponding to the proper field current to give unity power factor. The factor which does change is the current.

The synchronous motor is started without field excitation. It may be started in either of two ways, by an external means, as a small motor, a waterwheel, etc., or by utilizing its more or less prominent induction motor characteristics. The first of these requires no discussion, as it is easily accomplished by use of a small direct-connected unit or even by belt drive.

The field poles of the synchronous motor present either solid or laminated faces to the armature flux. When solid poles are used the eddy currents in the pole faces are excessive and with the hysteresis give a considerable starting torque similar to the condition existing in the induction motor, except that there are no definite low-resistance copper conductors for the secondary current. It is evident that this effect may be increased by the addition of such conductors and, nowadays, the synchronous motors are always built with some such additional device. It may be collars around the poles and bridges across the gap between pole tips, or the later form may be used, a partial squirrel-cage winding imbedded in the pole faces, with or without parallel bars in the gap between tips. The bars imbedded in the pole face may be interconnected as a grid. The presence of bars in the open area between pole tips is of questionable value and is apt to make the machine somewhat noisy. Moreover, mechanical trouble may occur due to their displacement. The bars are preferably pushed through closed slots, the pole face thus being smooth.

The average synchronous motor will start with about 30 per cent. full load torque at voltage ranging from 30 to 60 per cent., depending upon the constants of the motor and the load started. The current taken may be less than normal load current or it may be 50 to 100 per cent. in excess of the normal load value. No very large load may be started by the motor, however.

As the motor approaches synchronism, the induction motor characteristics become less important and the definite salient polar construction of the field exerts a decided influence tending to pull the machine into full synchronism, before a field current

is supplied. This action is more pronounced the nearer the machine has been brought to synchronism by its induction motor features. For this reason, the old style synchronous motors having no squirrel-cage winding may not be able to reach a point in speed where they can be pulled into synchronism unexcited. When field current is supplied, however, they will pull in properly. Upon the other hand, because of its damping effect, too strong a squirrel-cage characteristic may check the machine from quickly jumping into full synchronism, and prevent, rather than aid, the end sought. If the motor has reached full synchronism before the field is excited, it may well happen that the polarity due to field current comes up wrong in comparison to the armature flux. In this case; the motor must slip a pole. Before doing this, a heavy current is taken from the line. The actual displacement may occur with a very considerable oscillation back and forth across normal position until the revolving member has had time to settle down to a steady speed. When the machine will not pull into synchronism without field excitation, such an event as above does not occur. In either case, however, the shock to the system may be considerable and it is generally preferable to give field excitation before the motor armature has been supplied with full voltage. If this shock is great, the machine may fall farther from synchronism and stop.

After full speed has been attained and the field has been supplied full voltage may be applied to the armature. This necessitates throwing over from a tap to full coil on the autotransformer and means that the motor is disconnected from line for a short interval of time. This interval must be kept small or, with such machines as carry a fairly large friction load, the motor may lose enough headway to be badly out of phase when the armature is again supplied. In this latter case very heavy current demand may be made upon the line and serious results may include such phenomena as voltage drop, opening of oil switches, shutting down of motor or of substation apparatus, etc. In one such case that has been called to the writer's attention a large synchronous motor could never successfully be thrown upon the line, oil switches opening, at least upon the motor circuit, and sometimes upon the incoming lines of the station, shutting down the whole substation. It was found after numer-

ous trials, that by the hand-operated switches the motor could not be disconnected from the low-voltage tap and thrown upon the full coil in less than one second. By use of a synchroscope, it was determined that the motor would lose speed, with current off, at the rate corresponding to a displacement of 360 electrical degrees in 4 seconds. The trouble was explained at once, as the time interval with no power on was too great, corresponding to position loss of about 90 degrees. In such a case as this, it might be possible to *wait longer before reclosing the circuit*, a period corresponding to a little less than the 360 degrees, in which time the revolving field has lost two polar spans and is again about to come into proper relation to the armature. Unless the rate of retardation has become of considerable value, the machine could then undoubtedly be caught without serious disturbance.

The starting switches should be non-automatic, but the running switch should be automatic. For starting, the general arrangement is a combination of two switches called the magnetizing switch and the starting switch, between the two being placed the auto-transformer. This set of two switches and starting auto-transformer are shunted by the running switch, an automatic oil switch, which is thrown in after the field is on, as previously pointed out. The other two switches are then opened, leaving the starting apparatus dead.

A synchronous motor strives to keep in exact step with the supply circuit. This feature is at once the source of advantages and disadvantages. It is advantageous to have a motor of definite speed. But when there is a periodical fluctuation in the speed of the generator the motor just as certainly tries to follow every variation in frequency. If the generator is driven by a water wheel or by a steam turbine, the speed is quite uniform throughout the revolution. When the steam engine is used, however, especially the simple, single-cylinder engine, there is a variation in the speed of the generator during any one revolution. With a gas engine this is much greater. In fact, in the latter case it is advisable to put even upon the generator collars and bridges or squirrel-cage winding in order to limit, as far as possible, the fluctuations. If generators are run in parallel this is of considerable assistance toward steadying the speed. When, how-

ever, this variation in generator frequency corresponds to the period at which the motor armature would swing back and forth due to its natural frequency, every recurring impulse is added to the previous ones and the trouble continues to increase, giving wider and wider swings until a limit is reached where the eddy currents in the iron and the short-circuited currents in the bars increase in total energy consumed just as rapidly as the increase of energy supplied. If such a point is not reached the motor will fall out of step and come to standstill, opening the automatic circuit breakers in series with it. It must then be started as before.

In considering the means of eliminating this vigorous oscillation, or hunting, it is necessary to understand, definitely, the meaning of the term "natural frequency," when applied to a moving machine. Also, the numerous sources of disturbance must be recognized.

Mechanical motion may be uniformly continuous in a circle, the desired end in the case of the synchronous motor. It may also be oscillatory as in a pendulum. In the latter case, there is a definite periodicity depending upon two things, the length of the pendulum and the attraction of gravitation. In an electric motor or generator, these two kinds of motion may be combined, where the length of the pendulum becomes the radius of gyration of the revolving member and the attraction of gravitation is replaced by the magnetic attraction of the fields. The resultant motion might be represented by a curve consisting of a sine wave plus a constant. The natural period of this superimposed oscillation is determined, thus, by the radius of gyration and the magnetism. If, then, the revolving member receives a shock, there will occur a displacement from its normal position relative to the magnetism of the stationary member. To come back to this normal relation, the moving member oscillates backward and forward across the final position with gradually decreasing amplitude until the whole of the energy supplied by the shock has been absorbed by mechanical and electrical means. In the meantime, another shock may have been received. If so, and if it occurs at a certain epoch of the existing oscillation, the swing may be increased by it. With another epoch, the new shock may help to cancel the effects of the old one. It is evident that a

coincidence in periodicity of natural mechanical frequency of the motor and irregular impulses of the driving force will prove a serious thing if the energy of each shock is not exceedingly small compared to the rate of dissipation of that energy.

In general, there are three ways to limit or overcome hunting. The impulses may be eliminated, the coincidence of periods may be broken up or the rate of dissipation of the energy supplied by each shock may be increased. Frequently, it is necessary to resort to combinations of these in order to accomplish a satisfactory result.

To discuss these methods in reverse order, the supplying of collars, bridges, squirrel-cage winding or any other short-circuited device will give a much more rapid absorption of energy. These accessories dissipate no energy when the machine is in steady synchronous operation. In other words, they are absorption devices for the irregular impulses only and are known as damping devices or amortisseur devices. The induced currents in them oppose, by motor action, the force which causes their generation.

Synchronous motors should always be provided with these parts as a protection to speed regulation even where they are not required for starting, as previously described. It frequently occurs that trouble arises from some source other than the generator and one cannot count upon satisfactory operation under all conditions even with turbine-driven generators.

In breaking up the resonant relation between two members of a system, one member is always easily located—the troublesome one. The period of the synchronous motor, convertor, or alternator may be changed by a variation in the field excitation. In the analogy used above, this corresponds to varying the effect of gravitation upon the pendulum. The stronger the pull, the more rapid will be the vibration or oscillation. This has the disadvantage of affecting the power factor of the system and its use may be limited because of this secondary effect. The addition or elimination of a fly wheel may also be suggested, although this is a corrective step that must be undertaken carefully as it may even make things worse.

The cause of the disturbance is hardly ever as evident as its result. Frequently, it is only after a considerable amount of study and testing that the source is located.

Hunting is evidenced most quickly by the indicating meters, where the swing of the needle shows periodicity and, roughly, magnitudes of the disturbance. If the swing of the needle increases to a maximum and decreases to a minimum periodically it indicates two disturbances which "beat" against each other, having different frequencies and combining by exactly the same laws as do the air waves set up by two vibrating reeds. The number of needle swings per minute plus and minus the number of beats per minute will give the periodicities of the two disturbing factors of the system. It is then necessary to locate a moving member of the system which has the frequency noted. It may be found that the motor hunts against engine speed, engine governor, piston impulses of gas or steam engine, other motors or synchronous convertors. The parallel operating motors or convertors may be located in different substations and still affect each other.

Naturally, the proper corrective measure for hunting is to eliminate the irregular impulse received and the means of doing so depends upon from what it is found to come. Engine variations are generally taken care of by fly wheels. Governors are changed in either direction, making them more sensitive or less sensitive as may be required. Dashpots frequently help to keep the governor from over-reaching. As before mentioned, hunting between similar units may be handled by breaking up the coincidence of period. The first place to go to attempt this change in natural frequency is to the field of the motor or convertor. As a variation in field cannot be allowed beyond certain limits these extremes must be watched carefully.

When the field of a synchronous motor (or convertor) is varied, the armature current changes for a constant load. The curves expressing these relations are the "phase characteristics" or "V-curves." With any load, there is a certain value of field-ampere turns which gives minimum armature current. As field-ampere turns changes in either direction, the armature current increases by the vector addition of leading or lagging currents depending upon whether the excitation is made greater or made smaller than the specified value. The minimum value of armature current obtainable, naturally, corresponds to the greatest power factor, namely, 1.0. That is, with either over-excitation or under-excitation,

power factor is lowered. It is interesting to note the rate at which this lowering of power factor occurs. There are shown in Fig. 249 several phase characteristics for a two-phase synchronous motor, upon which are indicated the values of the power

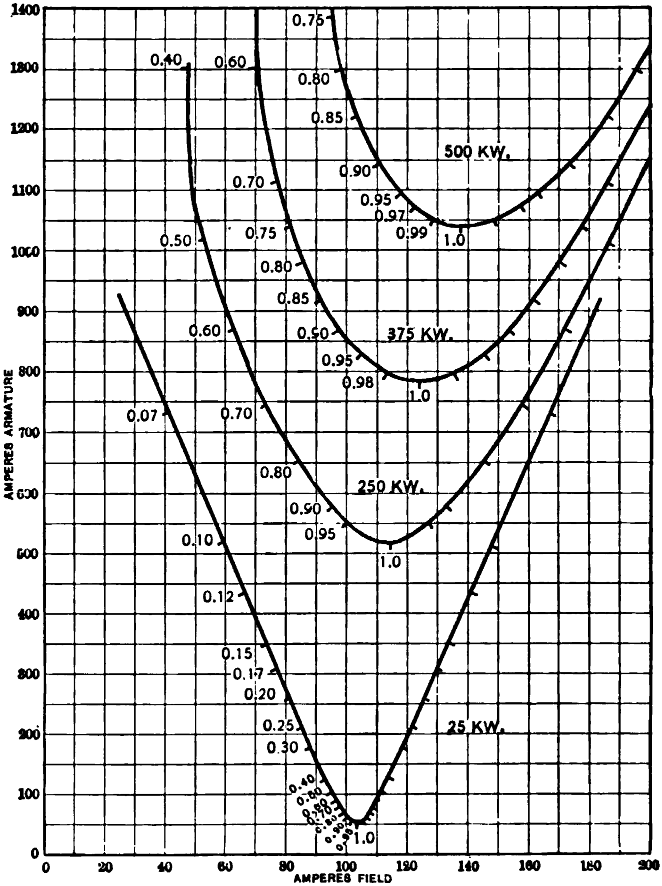

FIG. 249.—Phase characteristics of synchronous motor, showing power factor.

factor at various points. The machine is a 250-kilowatt motor and curves are calculated for 25 kilowatts, 250 kilowatts, 375 kilowatts and 500 kilowatts, that is, at loads of 10, 100, 150, and 200 per cent. With light load the change is very rapid. The minimum point upon the 10 per cent. load curve is for 50 amperes

armature with 104 amperes field. If field current is increased about 8 amperes, or 7.7 per cent., the armature current increases to such an extent that the power factor falls to 0.50. With normal load upon the machine an increase of the same number of amperes in the field will change the power factor to 0.98. This means, simply, that the increase in armature current due to the addition of the demagnetizing out-of-phase component is, in the latter case, a much lesser percentage of the total current. This point should be noticed, however, that within close limits an increase in field current of a certain amount, say 10 amperes, will demand a corresponding number of demagnetizing ampere turns upon the armature. That is, the out-of-phase component of armature current increases from zero at unity power factor, by the same amount for a given increase in field excitation, whatever the load. In order to bring into the system a certain corrective effect, the change in field amperes will be about the same for light or heavy load.

It is frequently the case that the power factor of a system is very low due to the nature of the load. This may occur during the whole day because of small induction motor-driven units. In such cases the power factor may hover around 0.70. Again, the low power factor may occur only during a part of the day when the line is relieved of a considerable portion of its load. This might occur on the light load periods of a constant potential lighting system when the exciting current of the small transformers forms the greatest part of the load. Again, certain electric furnace work will give low-power factor. This is not the best condition for the operation of either line or generator and it is beneficial to both if the power factor may be brought back into the range between 0.90 and 0.95. Especially is this the case if the total kilovolt-amperes is large. And herein lies a special use for the synchronous motor.

When a synchronous motor is used to give a corrective current to a system it is called a *synchronous condenser*. It is seldom required and hardly ever economical that it should carry the correction of the power factor much beyond 0.90 and it must be remembered that it will always be used with over-excited field in order to obtain a leading current. A machine rated at 500 kilovolt-amperes at 1.0 power factor may not be able to

stand the heating attendant upon supplying 500 kilovolt-amperes at 0.70 power factor. The armature heating may remain the same while the field current has been pushed up to a severe overload condition. These corrective machines need not run light as they may carry some mechanical load, or, in the case of convertors, some direct-current load, and at the same time over-excitation will draw a leading current from the line. With the addition of a mechanically loaded motor running at over-excitation, both current components are beneficial to the power factor, as may be seen by the vector diagam of voltage and current components shown in Fig. 250. In this figure, the voltage is

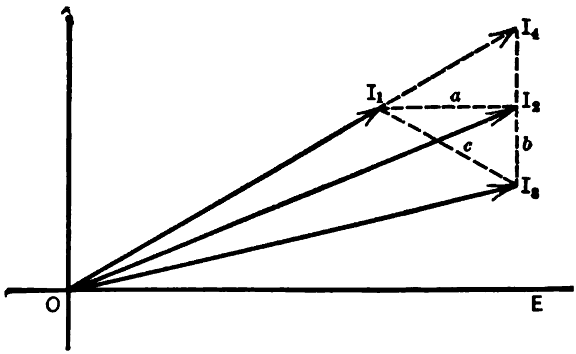

FIG. 250.—Effect of synchronous condenser.

taken as the initial line. I_1 is assumed as the current taken by the induction motor load, showing a lagging current. Now, if a load is taken by some synchronous motor at unity power factor it would be shown upon the same diagram by the addition to vector I_1 of vector a, giving I_2. The angular displacement of current in respect to voltage is decreased by a certain angle I_1OI_2. If the motor is allowed to carry the same load, but with a leading current due to over-excitation, besides the vector a there is a leading vector b due to the armature current, and this new component still further decreases the displacement between the electromotive force and the total current, i. e., the generator and line power factors are bettered. If the load added is small, the final value of current, I_3, may be smaller than was the original value I_1. To have carried the same extra load without change

of power factor would have required an increase of current from I_1 to I_4.

When load is distributed along the line, it is well to analyze each section of the line as well as the condition of the generator itself. An example may serve to illustrate several points. Take the distribution of load as expressed in kilovolt-amperes and spaced an shown in Fig. 251. The tabular form given in Table XXXIV shows the conditions existing in the successive sections, assuming a uniform power factor of 0.8 for the induction motor units. In the first part of the table is shown the total kilovolt-amperes of each section and its component parts, kilowatts and

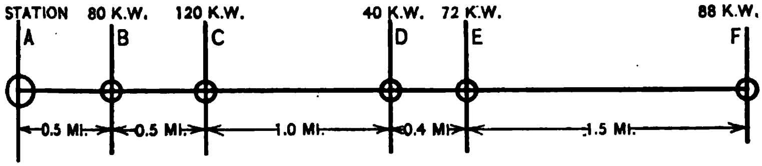

Fig. 251.—Application of synchronous condenser.

wattless kilovolt-amperes, for the condition of a total induction motor load. Part 2 shows similarly for each section the total and component parts when the induction motor at D is removed and a synchronous motor placed in its stead is over-excited to give 270 kilovolt-amperes loading. This would require a motor of about 273 kilovolt-amperes and would bring the power factor of the generator to unity.

In successive steps the motor capacity is lowered, keeping the load of 40 kilowatts constant but reducing the corrective current. As is seen, with considerable diminution in size of the synchronous motor, the rise in generator kilovolt-amperes is not great. In fact, bringing the wattless kilovolt-amperes supplied by motor down to only 80 kilovolt-amperes, which gives a motor rating of about 89.5 kilovolt-amperes, will cause a demand of only 443 kilovolt-amperes upon the generator. This is an increase of 43 kilovolt-amperes above that needed at unity power factor and the generator is supplying the line at a power factor of 0.902. As before pointed out, it would be uneconomical to attempt to bring the generator current completely into phase with the generator voltage, requiring unwarranted outlay.

Table XXXIV.—Application of Synchronous Condenser.

		A–B.	B–C.	C–D.	D–E.	E–F.
Ind. motor at D, carrying the 40-kw. load and requiring 30 kva. lagging. Gen. P. F. = 0.80.	Kw. Wattless kva. Kva. total	400 300 500	320 240 400	200 150 250	160 120 200	88 66 110
Synch. mot. at D, carrying the 40-kw. load and requiring 270 wattless kva. leading. Gen. P. F. = 1.0. Synch. mot. P. F. = 0.147.	Kw. Wattless kva. Kva. total	400 0 400	320 −60 326	200 −150 250	160 120 200	88 66 110
Synch. mot. at D, carrying the 40-kw. load and requiring 210 wattless kva. leading. Gen. P. F. = 0.988. Synch. mot. P. F. = 0.187.	Kw. Wattless kva. Kva. total	400 60 405	320 0 320	200 − 90 219	160 120 200	88 66 110
Synch. mot. at D, carrying the 40-kw. load and requiring 120 wattless kva. leading. Gen. P. F. = 0.936. Synch. mot. P. F. = 0.317.	Kw. Wattless kva. Kva. total	400 150 427	320 90 333	200 0 200	160 120 200	88 66 110
Synch. mot. at D, carrying the 40-kw. load and requiring 100 wattless kva. leading. Gen. P. F. = 0.92. Synch. mot. P. F. = 0.372.	Kw. Wattless kva. Kva. total	400 170 435	320 110 338	200 20 201	160 120 200	88 66 110

Table XXXIV.—Application of Synchronous Condenser.—Continued.

		A–B.	B–C.	C–D.	D–E.	E–F.
Synch. mot. at D, carrying the 40-kw. load and requiring 80 wattless kva. leading. Gen. P. F.=0.902. Synch. mot. P. F.=0.447.	Kw.	400	320	200	160	88
	Wattless kva.	190	130	40	120	66
	Kva. total	443	345	204	200	110

Alternating-current Commutator Motors.—The use of alternating-current commutator motors is, to a certain extent, special, as yet. The direct current motor, as a machine, is better in numerous respects. The former combines certain weak points of both alternating-current and direct-current practice, namely, the intermittent armature current and field current of alternating-current machines and the commutator of direct-current machines. Moreover, the commutator introduces here a bad feature not present in direct-current practice. This is the tendency to sparking under the brushes at standstill due to the transformer action between the field and the armature coils short-circuited by the brushes. The use of alternating-current commutator motors is thus justified only upon other grounds than that of the motor itself. This is based upon the demands of the distributing system where alternating current is much to be preferred.

The characteristics of these motors are fairly similar to those of the direct-current series motor, and, consequently, they have not attained importance except in railway work. Here, not only are their general characteristics suitable but the distributing system for interurban or suburban lines is more economically supplied by alternating current. They are, essentially, variable speed motors and have no speed limitation at synchronous value. The term "synchronism" has, for them, no more than a mathematical meaning. Depending upon the running speed above or below this point, however, different types of alternating-current motors have different peculiarities of operation. For example,

the repulsion motor has good commutation below synchronous speed and poor commutation above that point. Upon the other hand, the compensated series motor has poor commutation below synchronism, is fair at synchronism and gives good operation above that speed.

Direct-current motors are of two distinct types, shunt and series, so called from the type of field winding used. The use of a shunt field coil, however, does not preclude the use of a series coil as well, and during design the relative strength of these two field windings may be adjusted at will. The distinctive features of the shunt motor may, therefore, gradually shade off toward those of the series motor and eventually give place to the latter as the design changes. The whole range between the two extremes becomes available for any particular kind of work demanding it.

The plain shunt motor is a constant-speed machine. That is, with change of load the speed remains about the same. Steinmetz, in his book, "Elements of Electrical Engineering," shows that the actual change in speed as load increases depends upon what point of the saturation curve the motor is running upon. With over-saturation, the speed curve will droop, while with under saturation it may eventually rise quite appreciably. A change in voltage of the circuit upon which such a motor is running, may, therefore, quite seriously affect the speed characteristics of the motor because of the change in flux density caused thereby.

With change in voltage supply, total flux varies, which affects counter electromotive force and armature current. The net result, over a considerable range from normal voltage, is to decrease the speed at which a motor will carry a constant load with reduced voltage, the contrary change occurring for rise in voltage.

Shunt-wound machines may be designed to allow a considerable variation in excitation with no change in voltage supply to the armature. This gives an adjustable speed motor. If field excitation is decreased, the counter electromotive force of the motor for the same speed will fall off. This would rapidly increase the armature current and give increased torque. The greater torque is evidenced by the increase in speed. The

decrease in field current, therefore, increases speed. If, then, the machine is so designed as to allow a considerable change in field current, a corresponding variation in speed may be attained. After once adjusting the excitation the motor runs at the new speed as an approximately constant-speed motor, of course.

Varying speed motors, or those in which the speed varies with change of load, are of the series type. Here the excitation current and the field current are the same, so that with decreasing load there is decreasing field-excitation current and the motor speeds up in order to limit the armature current by a greater counter electromotive force. Speed rises rapidly, therefore, with decreasing load, and if load becomes too small the motor will reach a speed dangerous to its rotating member. As a consequence, this type of motor should never be used where there is any possibility of its load being suddenly disconnected, but it is suitable for any load which will build up with increasing speed. That is, a series motor should not carry a belted load (where the belt may fly off) nor drive a generator (where the circuit breakers may open) but it is well suited to railway work where heavy torque is required at standstill and is here furnished by virtue of the large armature current and heavy field excitation which exist before any counter electromotive force cuts them down. This gives a decreasing torque and decreasing power output with increasing speed.

For certain kinds of service, the two extremes just described, the shunt motor and the series motor, may both be improved upon by mingling their characteristics. For example, a light shunt field might be added to a series motor in order to limit its no-load speed. Or a light series field might give to the otherwise straight shunt motor the needed increase of torque at starting. Such machines are *compound wound motors.*

As before stated, any degree of compounding may be practised which is suitable for the load carried. In general, then, the compound wound motors have heavier starting torque than shunt machines, may be adjusted to different speeds by the shunt field and when so adjusted fall off in speed somewhat with increasing load. They are suitable for use where constant speed is not requisite but some variation may be allowed; where considerable starting torque may be required, as to drive line shaft-

ing; where torque varies considerably in the course of a cycle, as with pumps, punches, etc.; where the voltage is unsteady, as for shop motors upon a railway circuit. If desired, the series coil may be used for starting and then cut out of circuit for normal shunt-winding operation.

Compensating Windings.—As load is taken by a motor (or generator) the armature current increases. This gives a magnetomotive force of armature ampere-turns opposed to that of the field coils. This effect, known as armature reaction, will be in the direction of the brushes.

Depending, therefore, upon the brush position in respect to mechanical neutral position there will be *cross-magnetization* and *demagnetization.* The former has the effect of combining with the field flux and shifting the neutral point. The latter overcomes a part of the magnetizing effect of the field winding. A series coil added to the field can counteract the demagnetization but it does not influence the cross magnetomotive force. Inasmuch as the armature winding is distributed, a concentrated winding will not completely compensate for the armature reaction. A *compensating winding,* therefore, is a winding distributed in such a manner that its effective magnetomotive force, point by point, around the periphery, equals and opposes that of the armature circuits. It is series excited. The coils are laid in the pole faces, slots being prepared for their reception. Where there are definite pole pieces, this leaves a gap in the compensating winding distribution between pole pieces.

With a distributed field winding upon a continuous field structure, more nearly complete compensation is attainable. With good compensation a change in load will not shift the neutral and hence the brushes will be upon neutral without altering their position. This permits great variation in load without having to shift brushes. It also permits change in field excitation and, hence, speed regulation. Moreover, the properly proportioned compensating winding leaves the flux distribution the same for no load as for full load. This is important in that the counter electromotive force per coil of armature winding does not become excessive at certain points upon the periphery due to concentration of flux at that point. With excessive counter electromotive force or "volts per coil" there is great liability to

arc-overs which, when once started, may extend around from brush to brush.

Commutating Poles.—Without the use of the above extended construction commutation would be poor with change of load unless brushes were shifted to the new neutral. Another scheme for providing for good commutation is to supply a cross-magnetizing field opposed to that of the armature and of just sufficient strength to keep the neutral point fixed. This is accomplished by the use of small poles midway between the main poles and known as commutating poles or interpoles. (The former name is the better because it is applicable only to such a device while the latter term may be confused with certain forms of "split-pole" construction, where there is a small portion of the main pole set off from the pole piece itself.)

The office of the commutating pole is, therefore, to counterbalance the effect of armature reaction at one point in the periphery, only—the commutation point. It makes possible good commutation without change of brush position and with change in excitation, and, hence, speed. This is the same as with the compensating winding but beyond this there is a difference. With the commutating pole, point by point flux distribution changes and wave distortion occurs. There will occur at points certain changes in flux density which are accountable for similar variations in counter electromotive force. Voltage per coil may become excessive at one point of the armature and very low at another point, with the result that flashing occurs. This would probably be most pronounced at starting or upon a sudden increase of load as at these times the series excited commutating pole supplies excessive flux and distortion is greatest. Again, with weakened field for high-speed running, a sudden increase in load will have a greater influence upon flux distribution than it would with a stiff main field.

Commutating poles are placed upon motors, generators and convertors. They are especially effective in any motor where speed or load may change considerably. They are used in railway motors, hoisting motors, adjustable-speed motors, etc. So, also, are they productive of good results upon synchronous convertors, because these machines are most frequently installed upon railway systems, a load which varies greatly and rapidly.

Motor Applications.—With all of these different types of motors and their varying and overlapping characteristics, the selection of a suitable motor for a specified purpose becomes a study of the service required and the adaptation thereto of a proper machine. A mere figure giving the horse-power to be developed by the motor is too bare a statement to be of very much value. Naturally, there is first required a statement of the details of power supply available, alternating current, direct current, voltage, frequency, etc. The characteristics of the load to be carried will determine the starting torque, maximum power, intermittency of load with time elements of interruptions, variation in load with time elements, speed control required, attendance, etc. The location of the motor will determine whether it must be enclosed or not, as in wet places or in dusty places. It will likewise determine the kind of ventilation necessary.

When several machines are to be motor-driven it remains to be determined whether they should be grouped and driven by one motor through line shafting or separated and given individual motors. Flexibility and high individual efficiency for machines in constant use under varying conditions demand separate motoring. Where all load units are to be constantly operated under similar conditions and are conveniently assembled, group-drive has a strong case. With intermittent use of many machines —say of an hour or so during a day—if these machines are to be used at different times, economy of installation suggests using the same motor for each if their characteristic demands are similar. Where other things appear about equal, the loss due to a long line shaft with belting constitutes a strong argument against group drive, as does also the problem of proper illumination in a room with numerous belts.

When estimating the size of the motor to be installed, it is not proper to allow for future growth unless it is known that this will occur immediately. The reason is plain if we look at the efficiency curves (and power factor curves for alternating-current service) of the motors. There is a definite point somewhere around normal load where these curves are a maximum. Above normal load they do not change rapidly, but below it they fall off, generally, quite rapidly. A motor too large for its load is, therefore, an inefficient unit. Upon alternating-current systems

the power factor may suffer very seriously on account of bad practice in this respect. It is known as "over-motoring."

Although it is not possible to classify rigorously the different types of motor applications owing to the endless difference in details, the following grouping is suggestive of recent practice in many situations with quite varied demands. It is a very noticeable fact that the induction motor is one of the most usable machines we have, being built in all sizes from a small fraction of a horse-power to several thousand horse-power. Moreover, it is valuable in damp places, dusty places and localities where other machines might be sources of danger. As examples of these conditions we may cite, respectively, instances where induction motors driving pumps have been flooded but continued to operate and pump themselves dry; or where the motor is dust covered as in cement mills; or where a sparking commutator might set fire to gases or fumes, powder or even the finely divided flour dust in a mill. Its electrical characteristics are inferior to those of the synchronous motor and the latter should be used wherever possible, especially in large sizes.

MOTOR APPLICATIONS.

Induction Motors.

Concrete mixer.
Clay mixer.
Cinder grinder.
Grindstone.
Band saw.
Circular saw
Jig saw.
Wood planer.
Shaper.
Mortiser.
Moulding machine.
Milling machine.
Reamer.
House pump.
Fire pump.
Centrifugal pump.
Conveyor.
Grain shovel
Sign flasher.
Mill motors (25~. low speed for reversing).

Ventilating fan.
Blower.
Refrigerating plant.
Textile mills.
- Spinning.
- Weaving.
- Winding.

Laundry.
- Washing machine.
- Mangle.
- Smoothing iron.
- Centrifugal dryer.

Household.
- Dough mixer.
- Egg beater.
- Ice cream freezer.
- Meat grinder.
- Bread cutter.
- Sewing machine motor.
- Vacuum cleaner.
- Floor polisher.

Synchronous Motors.

Air compressor.
Synchronous condenser.
Centrifugal pump.
Motor generator.
Frequency changer.

Direct-current Shunt Motors.

Fire pump.
Centrifugal air compressor.
Churn.
Refrigerator.
Gas washer.
Ventilating fan.
Laundry (as ind. motor).
Household (as ind. motor).
Paper mills.

Direct-current Series Motors.

Air compressor.
Hoist.
Mill motors.
Railway.
Excavator.
Winch.

Direct-current Compound Wound Motors.

Drop hammer.
Punch press.
Shears.
Separator.
Printing press.
Planer.
Rock drill.
Conveyor.
Bending roll.
Plunger pump.
Slotter.
Elevator.

CHAPTER XII.

MEASUREMENTS.

The principal types of meters employed for given purposes are indicated below, with some of their most important sources of error.

Ammeters of the *moving coil type* are, fundamentally, made up of a permanent field magnet, a moving coil placed in the field of the magnet and carrying the pointer and a damping device to restrict the sensitivity of the instrument to rapid changes. This latter device may be a fixed, metal core within the moving coil, the induced eddy currents therein opposing rapid oscillation of the coil itself.

It will be seen that any factor disturbing the field strength becomes a source of error. Not only may the meter accuracy be temporarily affected, but the permanent magnets themselves may be disturbed to such an extent that the reading is always incorrect. If the meter is used upon alternating current the frequency also affects the reading. It should, therefore, be calibrated for the frequency for which it is to be used.

Ammeters of the *moving iron type* employ the principle of the solenoid. They may be used upon alternating current or direct current, but, as they depend upon the strength of field set up by the current in the fixed coil, external fields will temporarily vitiate the readings. The calibration should be made with current of the same frequency as that upon which the instrument is to be used. Wave form also effects variations in readings.

Induction ammeters depend upon transformer action between a coil as primary and a metal disc as secondary, in the latter of which eddy currents are produced. The torque is opposed by a spring which keeps the disc in the position where spring and torque balance. Here, again, frequency and wave form are of prime importance in calibration and use of the meter.

The *hot wire ammeter* depends for its action upon the expansion produced in a wire with rise in temperature. To a fixed current

corresponds a fixed i^2r loss in the wire, which loss occurs in the heat radiated from its surface. But, as radiation rate increases rapidly with rise in temperature, there will be a fixed temperature for a given current. That is, by carefully measuring the expansion and contraction of the current carrying wire, the meter may be calibrated to read amperes. With alternating current this will be the effective value because it is a measure of the i^2r loss. It is independent of wave form, magnetic field, frequency, etc., at least over a wide range of frequency, unless auxiliary shunts are used.

In all types of ammeters, the current carrying coil should have low resistance, in order to dissipate only a small amount of energy therein. The motion of the pointer carried by one element or the other may be opposed by spring or by gravitation. The spring is to be preferred, as its use avoids the necessity of accurate placing of the meter upon the board.

Modern meters are protected from magnetic disturbances by suitable iron cases, whether they are ammeters, voltmeters, or wattmeters.

Voltmeters may be of somewhat the same general types as are the ammeters and, when so constructed, they have the same limitations as regards frequency of alternations, external fields, wave form, position, etc. The coil, however, must be of high resistance in order that the current taken may be small.

Besides the forms known as the *moving coil type*, the *induction type*, the *hot wire type*, etc., there are other means of measurement not open to current measurements as well. The electrometer, for the determination of high-voltage values is frequently known as the *electrostatic voltmeter*. It consists of parallel vanes, plates, or boxes which receive charges from line or are connected to line and to ground. The moving member, or needle, is suspended by a fine wire. To increase the sensitivity of this device, the plates are placed closer together and increased in number. Despite these methods, the meter is not suitable for ordinary low voltages.

Another method which is employed very frequently in commercial measurements is that of the *spark gap*. The voltage to be measured is put across the air gap between two needle points, a high resistance being inserted in series with the gap in order to limit the current rush when the arc follows a spark discharge.

For low voltages the needles should be fairly sharp, but for high voltages it seems to make little difference, as for a gap of 15 inches, a coarse needle appears to be as "sharp" as a cambric needle. The discharge occurs across the gap, the distance between needle points is measured and the voltage reading is taken from a standard curve. Data for the curve are given by the A. I. E. E. as in Table XXXV. With very sharp needles, the lower portion of the curve tends to straighten somewhat.

Table XXXV.—Spark Gap Voltages. (A. I. E. E.)

Kilovolts sq. root of mean square.	Distance		Kilovolts. sq. root of mean square.	Distance.	
	Inches.	Cms.		Inches.	Cms.
5	0.225	0.57	140	13.95	35.4
10	0.47	1.19	150	15.00	38.1
15	0.725	1.84	160	16.05	40.7
20	1.00	2.54	170	17.10	43.4
25	1.30	3.3	180	18.15	46.1
30	1.625	4.1	190	19.20	48.8
35	2.00	5.1	200	20.25	51.4
40	2.45	6.2	210	21.30	54.1
45	2.95	7.5	220	22.35	56.8
50	3.55	9.0	230	23.40	59.4
60	4.65	11.8	240	24.45	62.1
70	5.85	14.9	250	25.50	64.7
80	7.10	18.0	260	26.50	67.3
90	8.35	21.2	270	27.50	69.8
100	9.60	24.4	280	28.50	72.4
110	10.75	27.3	290	29.50	74.9
120	11.85	30.1	300	30.50	77.4
130	12.90	32.8			

Power and Energy Meters.—In commercial work, accurate measurement of current or of voltage is seldom so important as is the determination of their effective product, for it is upon the basis of watt-hour consumption that payment for energy is made. Only in the case of direct current is this product obtain-

able by the factors of current and voltage themselves, so that, in order to check the direct reading of a wattmeter, the alternating-current circuit *power factor* must be read also. This method of checking is not valuable because it introduces so many instrument errors, errors of reading, etc., that no great dependence may be put in the final product. More especially is this true when we reach polyphase circuits, by which method the great bulk of power is handled.

The wattmeter[1] consists of two coils, a current coil and a potential coil, inductively related, a pointer being carried by the moving element (which is the potential coil). The motion of the pointer is opposed by a spring. A high non-inductive resistance is necessary in the circuit of the potential coil, being assembled as a part of the meter. In the watt-hour meter, the motion of the coil is opposed, not by a spring, but by a disc placed in a permanent magnetic field, the motion of which disc through the field generates eddy currents tending to limit the speed of rotation. The moving coil must be changed in detail of construction so that its motion does not take it out of the inductive relation with the series coil. This gives the moving element the nature of an armature with commutator. The number of revolutions is counted upon dials, the dial reading multiplied by some constant of the meter giving the watt-hour consumption.

In connecting a wattmeter or a watt-hour meter to a single-phase circuit, there are several errors which may separately appear in the reading. If the potential coil is connected across load and current coil, as in Fig. 252, the power read by the wattmeter will be that expended in the *load and the meter* as the *ir* drop in the current coil is included in the potential difference. If the leads running to the meter are long, this may be of considerable importance. Some gain in accuracy would be made if the voltmeter lead, now connected at B, should be attached at C. Still

[1] Unfortunately, there is a general looseness in the use of terms applied to power meters and energy meters. An instrument to measure and to indicate upon a scale the average amount of power being used by a circuit *should* be called a *wattmeter*. A meter which records the successive values by curve tracing apparatus *should* be called a *recording wattmeter*. An instrument which integrates or sums these readings, giving a dial record thereof, *should* be called an *integrating wattmeter* or a *watt-hour meter*. But this is not wholly in accord with practice. The term "wattmeter" is quite commonly heard used for the device for measuring watt-hours or energy. It is frequently qualified by the terms "recording," "indicating" or "integrating," used interchangeably. Such a confusion of terminology should not be allowed to continue.

better would it be to connect it at D. If there is much drop in DE due to heavy current the voltmeter lead must be carried back to E. This, in turn, introduces a new error, present when either of the points D and E is used. The current in the series coil now includes that taken by the potential coil. Generally speaking, however the connection at E is to be preferred, introducing

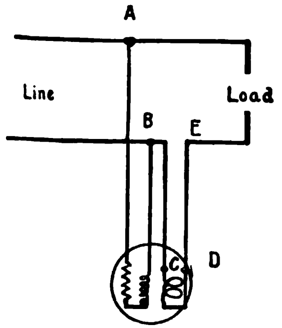

FIG. 252.—Single-phase wattmeter connections.

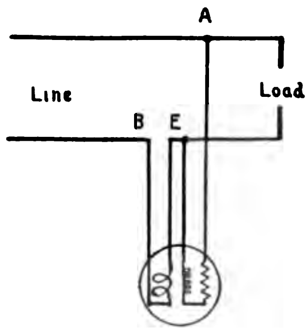

FIG. 253.—Single-phase wattmeter connections.

a lesser error than any of the other connections shown. Figure 253 gives, therefore, the recommended conditions.

When polyphase circuits are to be metered, the simplest (and least frequently met) condition is the balanced load. When this condition exists in three-phase work, the measurement of

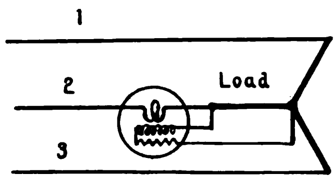

FIG. 254.—Single-phase wattmeter on three-phase Y-circuit.

power in one line or leg will give one-third of the total power developed. To measure this, the current coil of the meter carries line current and the potential coil is placed across line-to-neutral (Fig. 254) If the load is not of such a nature as will give a neutral point, a polyphase star connection of resistances can be supplied in order to present a true neutral point. The arrange-

ment is shown in Fig. 255 where *R,R,R,* are the star connected resistances, very accurately balanced in values.

The balanced △ condition may also be metered by the use of one meter and without the carefully adjusted three-phase resistance or reactance, provided a neutral tap is taken from one of the transformers. A meter connected as shown in Fig. 256 will read *one-half* of the entire load.

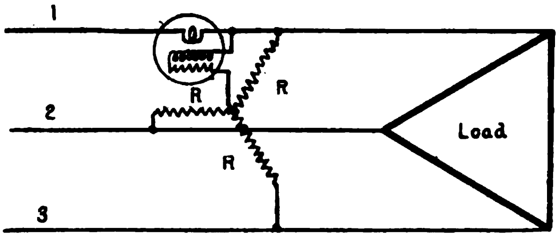

FIG. 255.—Single-phase wattmeter on three-phase delta circuit.

When the load is unbalanced in any respect the foregoing method is insufficient. The total load cannot be estimated from this single-meter reading, but at least two meters need to be installed, if load is to be read by single-phase meters, or they may be replaced by a single polyphase meter. To install two single-phase meters so that the *algebraic sum* of their readings may equal the total load connections should be made as shown in

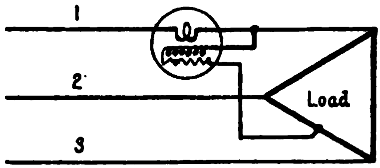

FIG. 256.—Single-phase wattmeter on three-phase delta circuit.

Fig. 257. With unbalanced load, or with balanced load and power factor less than unity, the readings of the two meters will not be similar. This is due to the fact that the voltage across each potential coil is not in phase with the current in the same meter even at unity power factor and with change of phase relations, displacement increases in one instrument and decreases in the other. The displacement may become sufficiently great

in one meter to reverse its direction of swing, in which case the larger reading is positive and the smaller is negative. There are two methods of recognizing this condition of dissimilarity of sign of the two quantities. When it is suspected that the power factor is low enough to effect this result, line number one may be opened, running the load as single phase. If meter reading *B* increases, it implies that meter *A* was indicating positive load. If reading *B* decreases, *A* was negative.

There are occasions, however, when it is not advisable to open one of the phases. In such a case the above test may be avoided

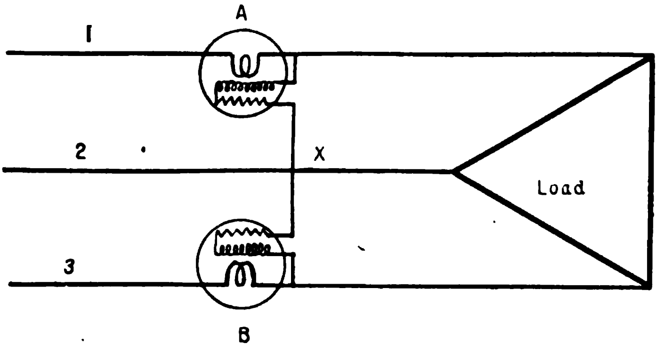

FIG. 257.—Two single-phase wattmeters on three-phase Y or Delta load.

by an equally simple one. The potential line (*X*) of one of the meters (*A*) running to the common line (2) is disconnected from that point and connected to the other outer line (3). If either meter was negative, the reconnected meter will reverse. Then, as before, the true power reading is obtained by taking the numerical difference between the two original readings.

Where the *power* is being read, this is quite satisfactory because indicating meters may be reversed in connection and left thus. Where *energy* is being read upon a varying load, the watt-hour meter must be as accurate when running backward as when running forward. It should, likewise, be accurate at light load and at overload. These conditions can be only approximated. It is, therefore, generally more satisfactory to combine the two meters into a single one, where the torques are in the same direction if signs are alike but are in opposite direction if signs differ. This is the much used *polyphase watt-hour meter*. It

may also be replaced by three single-phase watt-hour meters, each metering one phase.

Calibration and maintenance of meters is one of the very important items of operation, because an inaccuracy in the registration may very easily counterbalance numerous economies undertaken in the boiler-room, the generator-room, etc. Every installation should, therefore, be made with a view to the necessity of frequent and accurate calibrations of meters with a minimum expenditure of time and money. This is a process in which the single-phase instrument has the advantage over the polyphase instrument. The former may be interchanged, connected in series, etc., being tested, thus, at the same time and furnishing handy checks upon each other.

Where meter terminals may be connected directly to the circuits to be metered, more accurate readings may be obtained than in the case of very heavy currents or very high voltages.

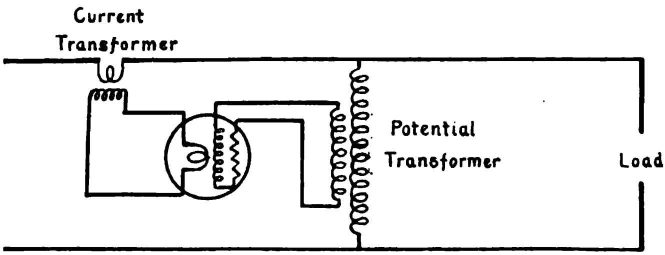

FIG. 258.—Wattmeter with transformers.

In the latter circumstances, there are two possible methods of measurement depending upon the magnitude of the reduction necessary.

If a moderate reduction of voltage is sufficient, a multiplier may be used in series with the potential coil. A similar reduction in current may be obtained by use of a shunt. These processes are not so accurate as the direct method but are still within the limits of very small errors.

When a considerable reduction becomes necessary, the *potential transformer* and the *current transformer* (series transformer) are used. The former consists of a transformer of a large number of turns taking very low current. The primary is connected

across the lines, Fig. 258, the secondary being lead to the potential coil of the meter. An error is introduced here, by a certain amount of phase displacement due to the fact that the secondary voltage is not exactly 180 degrees from the primary voltage. Leakage flux, resistance drop and reactance drop vary with varying voltage and current and hence cannot be entirely compensated for.

The current transformer is built with few turns in order to introduce low voltage drop in the line. Its primary is connected directly in series with one of the mains, Fig. 258, the secondary leading to the meter current coil. This transformer also introduces errors due to phase displacement and variable ratio. The exciting current of the primary has no corresponding component in the secondary.

No transformer has perfect regulation and it is, therefore, impossible to correct for these variables except at some predetermined point in the load condition.

Frequency Meters.—There are several methods of measuring the frequency of current or voltage waves. One of these employs a synchronous motor and a speed counter. This will give the average frequency over the time speed is read.

Another type places in opposition two coils of different impedance characteristics. These impedances will vary in quantitative and relative values as the frequency changes. The coils may be connected to oppose each other, the pointer being displaced by an amount corresponding to that frequency, *i.e.*, that relative value of impedances. Calibration is made and scale reading is taken directly in cycles per second. Wave form will affect the reading, hence, the instrument will need to be calibrated upon the same form of wave as that upon which it is to be used.

Another and better type depends upon the principle of mechanical resonance. Numerous reeds are assembled together, making a comb-shaped rack. Each reed has a particular vibration period corresponding to one value in the range to be covered by the instrument, as, for example, 55, 56, 57, . . . 60, . . . 63, 64, etc. An electromagnet receives energy from the circuit, producing an alternating field. The reed which has the same periodicity as the field will receive impulses synchronous with its swing and will vibrate through a wide angle. The scale reading

opposite this reed then gives the frequency of the circuit. The simplicity and reliability of this instrument are commendable.

Synchronism Indicators.—Aside from the use of lamps, there are various devices used to indicate when two pieces of apparatus are in synchronism. The result obtained includes more than that reached by lamps alone, for, with the use of the latter, the only information secured is that, when the lamps flicker, the machines are out of synchronism, in one direction or the other, the rapidity of the flicker indicating a measure of the speed difference. Changing speed of one of the machines and noting the results will determine which machine is fast and which is slow.

The ends to be attained by any indicator include

1. Indication of synchronism or relative frequencies, including direction of difference in speed.

2. Indication of phase relations, including direction of displacement and also phase rotation.

3. Indication of approximate voltage relations, at least. closely enough to permit throwing machines into parallel.

These points may be reached by the use of a phase-splitting device feeding the two coils placed upon an armature at right angles to each other. The armature circuits are excited from one phase of the machine being started. The field in which this armature is placed is excited by current from the bus bars. With this condition (the Lincoln synchronizer) the armature tends to revolve at such a speed that its magnetism is synchronous with that of the field reversals. This rotation is in one direction or the other, depending upon which magnetism reverses most rapidly. Hence, direction of rotation will show whether the machine is too high or too low in speed; the speed of rotation of a pointer attached to the armature will show how much different the frequencies are. Moreover, when the pointer comes to rest, if properly attached to the armature, it will show how much out of phase the two waves are, as they are running in synchronism.

Phase indicators will give the power factor of a system when there is no unbalancing of the load and when wave forms are not distorted, as they are in an arc circuit. Otherwise, they give only the phase relation.

The circuits of the instrument provide series coils and a shunt coil. The series coils are so arranged that they produce a rotating field. The shunt coil, being arranged to produce only an oscillating field, will tend to set itself in position such that its axis coincides with the direction that the rotating field has at the time of maximum shunt-coil field strength. The scale reading may be suitably prepared to read either angular displacement or power factor on undistorted systems.

Effective Value and Scale of Curves.—When a curve of voltage, etc., is obtained by reading successive values it may become necessary to calculate the effective value. Upon the other hand,

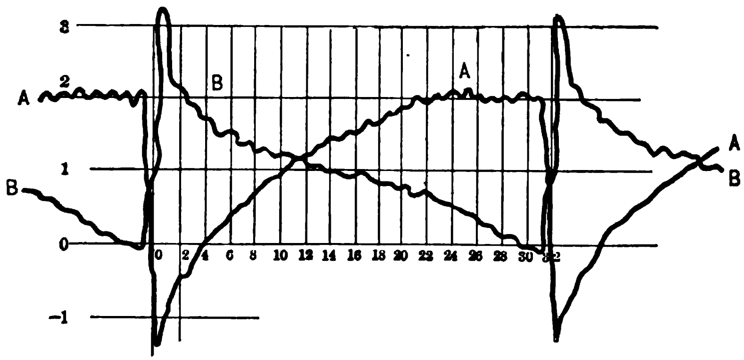

FIG. 259.—Determination of scale of curve.

when a curve is traced by oscillograph and an effective reading is taken by meter, it is necessary to estimate the scale to which the curve is drawn. These two processes are, in part, the reverse of each other and a solution of one will illustrate both.

Taking a given curve, to calculate the scale, we will use the curves A and B shown in Fig. 259, and the meter readings 14 amperes and 14.5 amperes respectively. The two curves A and B are oscillograms of the unbalanced currents existing in the two sides of a three-wire generator armature running under balanced load but with unequal resistances in the armature windings. This happens to be an abnormal condition but it will serve our purpose, nevertheless.

A scale is assumed and readings of the curve are taken in the assumed units at equal intervals for one complete cycle of this curve because there is no negative loop equivalent to the positive

loop. The scale is shown in the figure and the number of readings taken to cover the one cycle is 32. Ordinarily, it may be well to space these readings by 10 degrees, or some other integer. These readings are tabulated in the Table XXXVI for both curves A and B. In each case, the column marked y is the reading, to assumed scale. This value is squared and placed in a new column. The average values of the y^2s are taken, giving respectively:

$$\text{Avg. } y^2_A = 2.32,$$
$$\text{Avg. } y^2_B = 1.443.$$

Whence

$$\sqrt{\text{mean square } A} = 1.149 \text{ divisions},$$
$$\sqrt{\text{mean square } B} = 1.202 \text{ divisions},$$

or

$$\text{Effective } A = 1.149 \text{ divisions} = 14 \text{ amperes},$$
$$\text{Effective } B = 1.202 \text{ divisions} = 14.5 \text{ amperes}.$$

Hence

$$\text{Curve } A, \text{ one division} = 12.19 \text{ amperes},$$
$$\text{Curve } B, \text{ one division} = 12.06 \text{ amperes}.$$

This gives us a means of calculating the instantaneous values of current for the entire sweeps of the curves and final columns are added showing these instantaneous values in amperes.

The reverse of this process should be employed when the meter reading is not obtainable, but upon the oscillogram of the wave to be studied there is determined a scale by means of a known direct current. In this case, the instantaneous values are read in amperes and the effective value calculated therefrom.

Curve Analysis.—When an alternating or pulsating periodic wave is given it has been shown by Fourier that the wave may be represented by a series,

$$\begin{aligned} Y = a_0 + a_1 \cos\theta + a_2 \cos 2\theta + a_3 \cos 3\theta + \ldots \\ + b_1 \sin\theta + b_2 \sin 2\theta + b_3 \sin 3\theta + \ldots \end{aligned}$$

If the positive area enclosed equals the negative area enclosed, *i.e.*, if the wave is *alternating* as against *pulsating* and averages zero, the term a_0 disappears.

If the sequence of positive instantaneous values is duplicated by the sequence of negative values—*i.e.*, if the rectified negative

Table XXXVI.—Determination of Scale of Curve.

x	y_B	y^2_B	i_B	y_A	y^2_A	i_A
0	1.0	1/2(1.00)	12.06	−1.4	1/2(1.96)	−17.07
1	3.3	10.89	39.8	−1.0	1.00	−12.19
2	2.3	5.29	27.75	−0.5	0.25	− 6.09
3	1.95	3.80	23.5	−0.3	0.09	−3.66
4	1.7	2.89	20.5	0.0	0.00	0.00
5	1.5	2.25	18.1	0.2	0.04	2.44
6	1.5	2.25	18.1	0.35	0.10	4.26
7	1.35	1.82	16.3	0.5	0.25	6.09
8	1.3	1.69	15.67	0.6	0.36	7.31
9	1.3	1.69	15.67	0.8	0.64	9.75
10	1.2	1.44	14.47	0.9	0.81	10.96
11	1.2	1.44	14.47	1.1	1.21	13.4
12	1.2	1.44	14.47	1.25	1.56	15.22
13	1.05	1.10	12.67	1.35	1.82	16.45
14	1.0	1.00	12.06	1.45	2.11	17.67
15	0.9	0.81	10.84	1.45	2.11	17.67
16	0.95	0.91	11.45	1.55	2.40	18.9
17	0.85	0.72	10.24	1.7	2.89	20.72
18	0.8	0.64	9.65	1.65	2.72	20.1
19	0.8	0.64	9.65	1.75	3.06	21.34
20	0.75	0.56	9.05	1.85	3.42	22.55
21	0.7	0.49	8.44	1.95	3.80	23.76
22	0.65	0.42	7.84	2.00	4.00	24.38
23	0.55	0.31	6.63	2.05	4.10	25.0
24	0.5	0.25	6.03	2.1	4.41	25.6
25	0.4	0.16	4.82	2.1	4.41	25.6
26	0.3	0.09	3.62	2.05	4.10	25.0
27	0.2	0.04	1.41	2.05	4.10	25.0
28	0.1	0.01	1.21	2.05	4.10	25.0
29	0.1	0.01	1.21	2.0	4.00	24.38
30	−0.1	0.01	− 1.21	2.05	4.10	25.0
31	−0.2	0.04	− 2.41	2.1	4.41	25.6
32	1.0	1/2(1.00)	12.06	−1.4	1/2(1.96)	17.07
		32)46.10			32)74.37	
		1.443			2.32	
		1.202^2			1.15^2	

wave repeats the positive wave—the even harmonics disappear, and the equation is made up of only the odd harmonics, fundamental, third, fifth, seventh harmonics, etc.

It follows from this that, as nearly all ordinary waves are of this latter form, we may represent ordinary current waves or voltage waves by equations of the form

$$y = a_1 \cos\theta + a_3 \cos 3\theta + a_5 \cos 5\theta + \ldots + a_{2n+1} \cos (2n+1)\theta + \ldots$$
$$+ b_1 \sin\theta + b_3 \sin 3\theta + b_5 \sin 5\theta + \ldots + b_{2n+1} \sin (2n+1)\theta + \ldots$$

In this equation

a_{2n+1} is the maximum value of the cosine component of the $(2n+1)$th harmonic,

b_{2n+1} is the maximum value of the sine component of the same harmonic,

$$\sqrt{a_{2n+1}^2 + b_{2n+1}^2} = \text{maximum value of } (2n+1)\text{th harmonic},$$
$$\tfrac{1}{2}\sqrt{2}\sqrt{a_{2n+1}^2 + b_{2n+1}^2} = \text{effective value of } (2n+1)\text{th harmonic}.$$

Moreover, the effective value of the total wave is found by taking the square root of the sum of the squares of *all harmonics*.

Any given periodic wave may be analyzed and an approximate numerical equation may be developed for it, the degree of accuracy depending upon the accuracy of measurement of readings taken from the curve and also upon the number of harmonics considered. One process of determining the values of the coefficients of the terms in the general equation will be outlined although the development of the method and its proof will be omitted.

The curve is divided by equally spaced ordinates, say 10 degrees apart, and the ordinates read at these points. To find the fundamental wave these successive readings are multiplied by the values of $\cos\theta$ and $\sin\theta$ corresponding thereto.

It is convenient to prepare this in tabular form arranging data in columns as derived, thus:

θ	y_1	$\cos\theta$	$\sin\theta$	$y_1 \cos\theta$	$y_1 \sin\theta$
0	0	1.00	0.0	0.00	0.00
10	1.1	0.9848	0.1737	1.08	0.19
20	2.2	0.9397	0.3420	2.06	0.75
⋮	⋮	⋮	⋮	⋮	⋮

The average value of $y_1 \cos \theta$ equals one-half the value of a_1, hence

$$a_1 = 2 \text{ avg.}(y_1 \cos \theta).$$

Similarly,

$$b_1 = 2 \text{ avg.}(y_1 \sin \theta).$$

The fundamental wave is represented by

$$f(\theta_1) = a_1 \cos \theta + b_1 \sin \theta,$$

$$\sqrt{a_1^2 + b_1^2} = \text{maximum value.}$$

$$\tfrac{1}{2}\sqrt{2}\sqrt{a_1^2 + b_1^2} = \text{effective value.}$$

The values of a_1 and b_1 found are expressed in the same units as are the readings y_1 and, hence, are not, generally speaking, in amperes or volts, but are in mm., etc. The scale of the curve is yet to be determined.

Although it is not necessary to do so, it is well to take from the complete irregular wave the fundamental component just found before proceeding to find the next harmonics (Table XXXVII). This will be done by subtracting from the successive values of y_1 the products $a_1 \cos \theta$ and $b_1 \sin \theta$.

Calling this difference y_3, we have

$$y_3 = y_1 - (a_1 \cos \theta + b_1 \sin \theta) = y_1 - f(\theta_1).$$

To estimate the third harmonic, the preceding process is repeated except that the products now taken are $y_3 \cos 3\theta$ and $y_3 \sin 3\theta$, after which the equations hold

$$a_3 = 2 \text{ avg. } (y_3 \cos 3\theta)$$

$$b_3 = 2 \text{ avg. } (y_3 \sin 3\theta)$$

$$f(\theta_3) = a_3 \cos 3\theta + b_3 \sin 3\theta, \text{ the third harmonic.}$$

$$\sqrt{a_3^2 + b_3^2} = \text{maximum value of third harmon}$$

$$\tfrac{1}{2}\sqrt{2}\sqrt{a_3^2 + b_3^2} = \text{effective value of third harmonic.}$$

$$\Sigma_1^3 f(\theta_{2n+1}) = \text{total value of determined components.}$$

$$= f(\theta_1) + f(\theta_3).$$

$$y_5 = y_3 - f(\theta_3), \text{ harmonics, fifth and higher.}$$

The process may be continued for the solution of the fifth harmonics, etc., provided the curve represented by y_5 is large enough to warrant it. In order to make a concrete case of this process, a tabular form is attached in which a given wave, y_1, is analyzed for fundamental, third and fifth harmonics, and the

Table XXXVII.—Curve Analysis.

θ	y_1	$\cos\theta$	$\sin\theta$	$y_1\cos\theta$	$y_1\sin\theta$	$0.296\times\cos\theta$	$5.13\times\sin\theta$	$f(\theta_1)$	$y_3 = y_1 - f(\theta_1)$	$y_3\cos 3\theta$	$y_3\sin 3\theta$	$-0.497\times\cos 3\theta$
0	0.0	1.00	0.00	0.00	0.00	0.30	0.00	0.30	−0.30	0.000	0.000	−0.497
10	1.1	0.9848	0.1737	1.08	0.19	0.29	0.89	1.18	−0.08	−0.069	−0.040	−0.431
20	2.2	0.9397	0.3420	2.06	0.75	0.28	1.75	2.03	0.17	0.085	0.147	−0.249
30	3.05	0.8660	0.5000	2.62	1.53	0.26	2.57	2.81	0.24	0.000	0.240	0.000
40	3.9	0.7660	0.6428	2.99	2.51	0.23	3.30	3.53	0.37	−0.185	0.320	0.249
50	4.65	0.6428	0.7660	2.99	3.56	0.19	3.93	4.12	0.53	−0.459	0.265	0.431
60	5.2	0.5000	0.8660	2.60	4.50	0.15	4.43	4.58	0.62	−0.620	0.000	0.497
70	5.4	0.3420	0.9397	1.85	5.08	0.10	4.81	4.91	0.49	−0.424	−0.245	0.431
80	5.25	0.1737	0.9848	0.91	5.17	0.05	5.05	5.10	0.15	−0.075	−0.130	0.249
90	4.75	0.0000	1.0000	0.00	4.75	0.00	5.13	5.13	−0.38	0.000	0.380	0.000
100	4.1	−0.1737	0.9848	−0.71	4.04	−0.05	5.05	5.00	−0.90	−0.450	0.780	−0.249
110	3.85	−0.3420	0.9397	−1.32	3.62	−0.10	4.81	4.71	−0.86	−0.743	0.430	−0.431
120	3.72	−0.5000	0.8660	−1.86	3.22	−0.15	4.43	4.28	−0.56	−0.560	0.000	−0.497
130	3.61	−0.6428	0.7660	−2.32	2.77	−0.19	3.93	3.74	−0.13	−0.112	−0.065	−0.431
140	3.35	−0.7660	0.6428	−2.57	2.15	−0.23	3.30	3.07	0.28	0.140	0.242	−0.249
150	2.83	−0.8660	0.5000	−2.45	1.42	−0.26	2.57	2.31	0.52	0.000	0.520	0.000
160	2.13	−0.9397	0.3420	−2.00	0.73	−0.28	1.75	1.47	0.66	−0.330	0.571	0.249
170	1.23	−0.9848	0.1737	−1.21	0.21	−0.29	0.89	0.60	0.63	−0.545	0.315	0.431
180	0.0	−1.0000	0.0000	0.00	0.00	−0.30	0.00	−0.30	0.30	−0.300	0.000	0.497
				2.66	46.20					−4.477	3.610	

$a_1 = 0.296$; $b_1 = 5.13$
$\sqrt{a_1^2 + b_1^2} = 5.14$
Eff. value $= 3.63$

$a_3 = -0.497$; $b_3 = 0.401$
$\sqrt{a_3^2 + b_3^2} = 0.64$
Eff. value $= 0.45$

Table XXXVII. Curve Analysis.—(*Continued*).

θ	$0.401 \times \sin 3\theta$	$f(\theta_3)$	$f(\theta_1)-f(\theta_3)$	$y_5 = y_3 - f(\theta_3)$	$y_5 \cos 5\theta$	$y_5 \sin 5\theta$	$0.24 \times \cos 5\theta$	$0.022 \times \sin 5\theta$	$f(\theta_5)$	$\sum_1^3 f(\theta_{2n+1})$	y_7	y_1^2	y_7^2
0	0.000	−0.50	−0.20	0.20	0.200	0.000	0.240	0.000	0.24	0.04	−0.04	0.00	½(0.0016)
10	0.201	−0.23	0.95	0.15	0.097	0.115	0.155	0.017	0.17	1.12	−0.02	1.21	0.0004
20	0.348	0.10	2.13	0.07	−0.024	0.066	−0.042	0.022	−0.02	2.11	0.09	4.84	0.0081
30	0.401	0.40	3.21	−0.16	0.138	−0.080	−0.207	0.011	−0.20	3.01	0.04	9.30	0.0016
40	0.348	0.60	4.13	−0.23	0.216	0.078	−0.225	−0.008	−0.23	3.90	0.00	15.20	0.0000
50	0.201	0.63	4.75	−0.10	0.034	0.094	−0.082	−0.021	−0.10	4.65	0.00	21.60	0.0000
60	0.000	0.50	5.08	0.12	0.060	−0.104	0.120	−0.019	0.10	5.18	0.02	27.00	0.0004
70	−0.201	0.23	5.14	0.26	0.255	−0.046	0.236	−0.004	0.23	5.37	0.03	29.15	0.0009
80	−0.348	−0.10	5.00	0.25	0.191	0.161	0.184	0.014	0.20	5.20	0.05	27.50	0.0025
90	−0.401	−0.40	4.73	0.02	0.000	0.020	0.000	0.022	0.02	4.75	0.00	22.50	0.0000
100	−0.348	−0.60	4.40	−0.30	0.230	−0.193	−0.184	0.014	−0.17	4.23	−0.13	16.80	0.0169
110	−0.201	−0.63	4.08	−0.23	0.226	0.040	−0.236	−0.004	−0.24	3.84	0.01	14.80	0.0001
120	0.000	−0.50	3.78	−0.06	0.030	0.052	−0.120	−0.019	−0.14	3.64	0.06	13.80	0.0036
130	0.201	−0.23	3.51	0.10	0.034	−0.094	0.082	−0.021	−0.10	3.41	0.20	13.00	0.0400
140	0.348	0.10	3.17	0.18	0.169	−0.031	0.225	−0.008	0.22	3.39	−0.04	11.20	0.0016
150	0.401	0.40	2.71	0.12	0.104	0.060	0.207	0.011	0.24	2.95	−0.12	8.00	0.0144
160	0.348	0.60	2.07	0.06	0.010	0.059	0.042	0.022	0.06	2.13	0.00	4.53	0.0000
170	0.201	0.63	1.23	0.00	0.000	0.000	−0.155	0.017	−0.14	1.09	0.14	1.51	0.0196
180	0.000	0.50	0.20	−0.20	0.200	0.000	−0.240	0.000	−0.24	−0.04	0.04	0.00	½(0.0016)
					2.170	0.197						241.94	0.1116
												13.43	0.0062
												——2	——2
												3.67 −	0.08 −

$a_5 = 0.24$; $b_5 = 0.022$

$\sqrt{a_5^2 + b_5^2} = 0.24$

Eff. value $= 0.17$

remainder including harmonics of the seventh order and above are considered negligible because the total effective value thereof is slight (about 2 per cent. of the given wave). Curves are given showing the accuracy attained by the successive approxi-

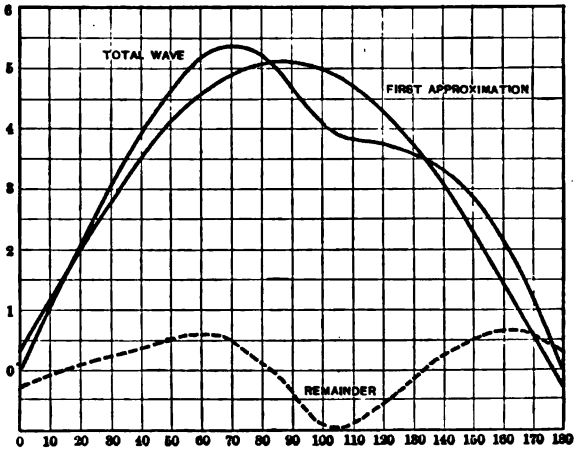

FIG. 260.—Curve analysis showing first approximation and remainder.

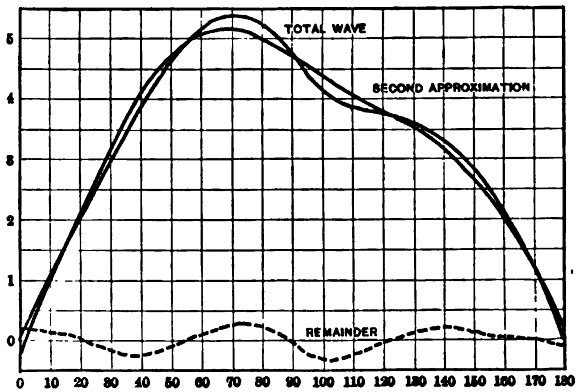

FIG. 261.—Curve analysis showing second approximation and remainder.

mations (Figs. 260, 261, 262). It will be seen from the data given that the effective values of the successive curves are

3.63 $=$ effective value of $f(\theta)_1$.
3.66 $=$ effective value of $\Sigma_1^3 f(\theta_{2n+1})$.
3.66+ $=$ effective value of $\Sigma_1^5 f(\theta_{2n+1})$.

While

$3.67- =$ effective value of original curve,

and

$0.08- =$ effective value of $\Sigma_7^\infty f(\theta_{2n+1})$, the part neglected.

If, then, the meter reading corresponding to the above wave is 180 amperes, the scale becomes

1 division	$=49$ amperes.
$f(\theta_1)$	$=178$ amperes.
$\Sigma_1^3 f(\theta_{2n+1})$	$=179.4$ amperes.
$\Sigma_1^5 f(\theta_{2n+1})$	$=179.5$ amperes.
$\Sigma_7^\infty f(\theta_{2n+1})$	$=3.92$ amperes.

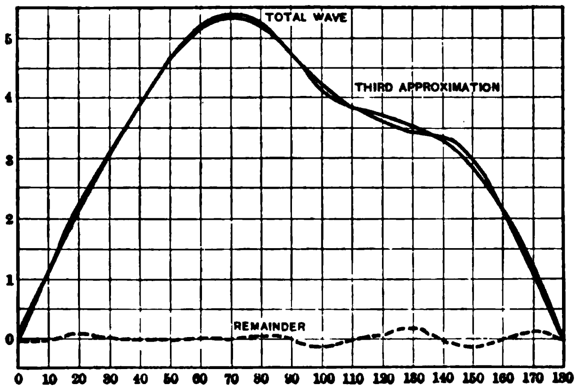

FIG. 262.—Curve analysis showing third approximation and remainder.

The equations are

Fundamental, $f(\theta_1) = 0.296 \cos \theta + 5.13 \sin \theta$.

Third harmonic, $f(\theta_3) = -0.497 \cos 3\theta + 0.401 \sin 3\theta$.

Fifth harmonic, $f(\theta_5) = 0.24 \cos 5\theta + 0.022 \sin 5\theta$.

and our approximation to the original wave is the sum of these three waves, namely

$$y_1 = 0.296 \cos \theta - 0.497 \cos 3\theta + 0.24 \cos 5\theta + 5.13 \sin \theta + 0.401 \sin 3\theta + 0.022 \sin 5\theta.$$

Curve Tracers and Oscillographs.—There are numerous forms of devices for recording the forms of waves and other varying phenomena. Two distinct classes of instruments are found.

One, generally spoken of as the curve tracer, requires a point-by-point determination of the successive values and is usable only when the phenomenon is recurrent. Considerable care is required in locating one point upon the curve and this is, therefore, a comparatively slow process, but a correspondingly accurate determination may be made with suitable devices.

Another form will record upon photographic film the sequence of values passed through as they occur, giving a complete record for only a few cycles of the event. This type is known as the oscillograph, the record as the oscillogram.

It will be seen, at once, that each process has individual characteristics making it peculiarly useful in certain fields.

The point-by-point method may be used with very slight expense in laboratory study of wave form and very satisfactory results obtained. The record gives an average curve as successive points are taken from distantly removed cycles of the phenomenon.

The oscillogram, on the other hand, might well be termed the "indicator card" of the electrical system. Its present usefulness in the solution of problems is already remarkable, but its availability for undertaking new investigations is scarcely appreciated. One is inclined to associate it with laboratory practice and the manufacturing shop. Here it is recognized as immensely useful. One great future development will, undoubtedly, depend upon its ability to analyze and locate trouble in the electrical system. There is room for a great deal of careful work along these lines.

The oscillograph consists, essentially, of the following parts:

> Vibrating galvanometer of short oscillation period.
> Light source with optical system.
> Photographic recording device.

It may likewise include

> Visualizing device, with synchronously driven mirror and a proper screen.

Details of these parts and their operation may be secured from an interesting article in Trans. A.I.E.E. Vol. XXIV upon "The Oscillograph and Its Uses" by L. T. Robinson, as may also much of the history of the apparatus.

Examples of its use may be seen by referring to a number of figures.

Figure 263 shows the records obtained upon the field and armature circuits of an alternating-current generator. The upper curve is for armature current, the lower for field current. When running at much reduced voltage (*i.e.*, a low field current), the armature is suddenly short-circuited. The armature current builds up to over 3000 amperes and pulsates over a gradually decreasing range, finally settling down to a fairly symmetrical wave. Field current, constant before the short-circuit, oscillates

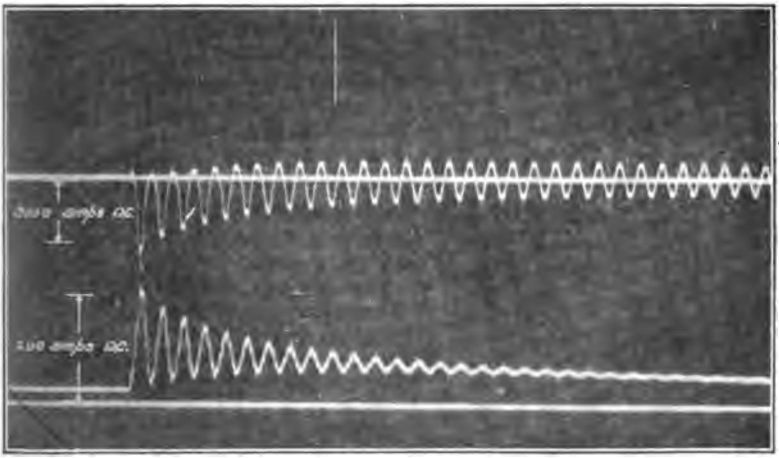

FIG. 263.—Short-circuit of generator carrying no load.

to large values due to its inductive relation to the armature current. The scale of the alternating armature current is shown by an ordinate representing 3000 amperes direct current. The scale of the direct field current is shown by a 200-ampere ordinate.

In Figure 264 an alternator running at part load and reduced voltage is suddenly short-circuited. The alternating current of the armature (upper curve) gives place to a high pulsating current gradually reducing to low values again. Wave shapes are affected markedly. The field current (lower curve) shows some pulsation to begin with, but is greatly affected by the enormous rise in armature current.

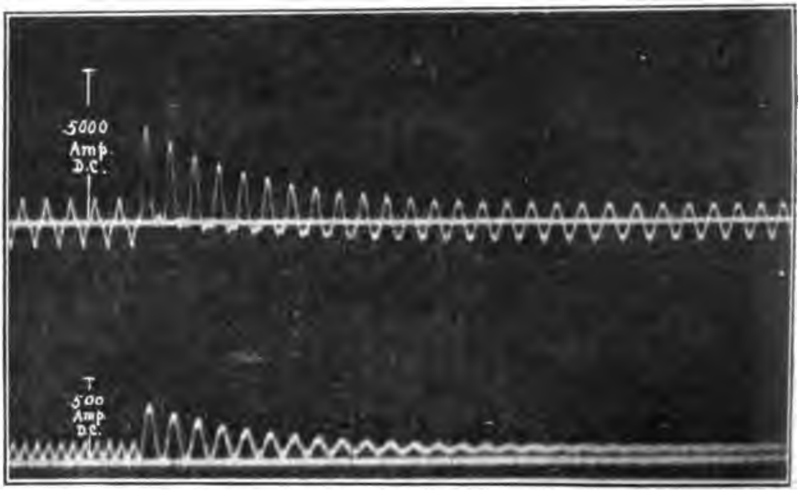

FIG. 264.—Short-circuit of generator carrying part load.

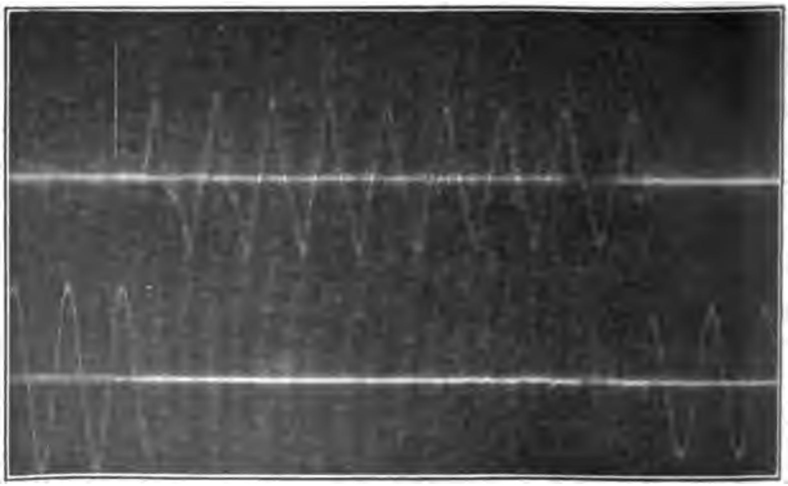

FIG. 265.—Opening of oil circuit breaker on alternating current.

In Fig. 265 the lower curve represents an alternating-current voltage wave. The circuit supplied is protected by an oil circuit breaker. The upper curve shows the current in the circuit when a short-circuit occurs, reducing voltage to zero, but allowing it to rise again immediately after the breaker opens. It will be noted that the circuit opens at the zero point of the current wave.

When a direct current is to be studied (Fig. 266) it is well to put upon the same record an alternating current of known frequency to serve as a time scale. Hence in blowing an aluminium

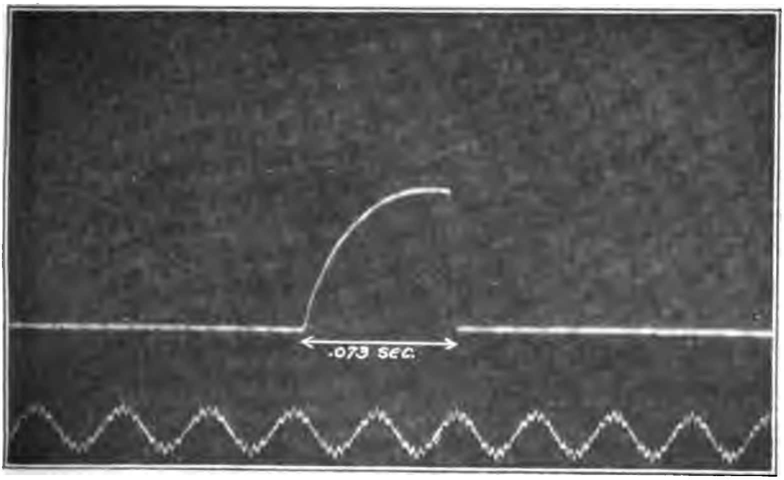

FIG. 266.—Blowing aluminium fuse on direct current.

fuse, as is shown, the time element between rise and fall of direct current is estimated from the 25-cycle current wave below.

Figure 267 shows a partial recovery of voltage after a fuse has opened the line upon an alternating-current circuit. The upper curve is current, the lower curve is voltage.

Finally (Fig. 268) there is shown a much slower record. The test is made upon a 60-cycle synchronous convertor by bringing it up to synchronism from the alternating-current end and later closing the field and allowing a considerable field current to flow immediately. There results a decided pulsation in the circuit. For lesser field currents this pulsation is less marked. It should

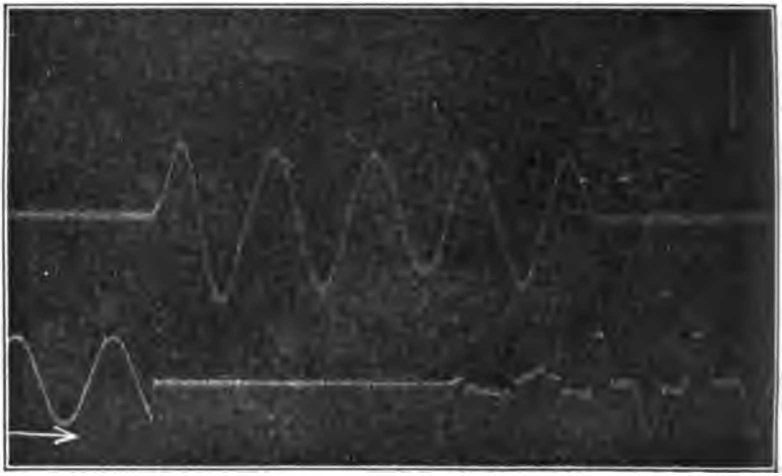

FIG. 267.—Recovery of alternating-current voltage after blowing a fuse.

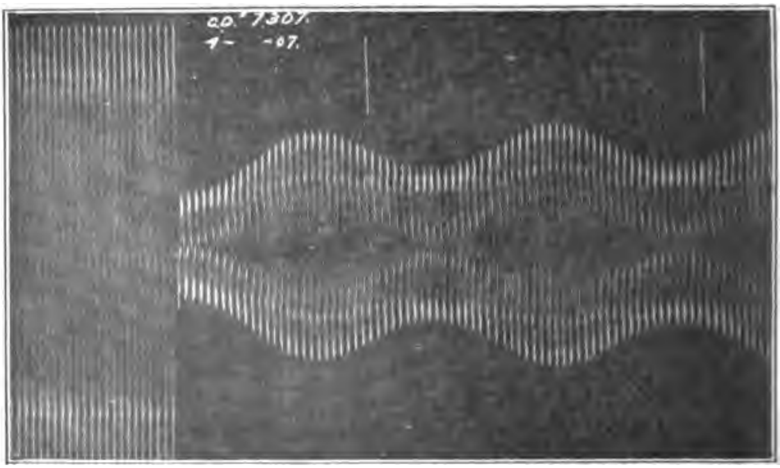

FIG. 268.—Pulsation of synchronous converter.

be noted that the period of the oscillation is about the time required for 32 cycles, that is, a little over half a second.

Demand Indicators.—As will be seen in the consideration of different methods of charging for energy, it becomes necessary, in connection with some systems, to know what maximum demand has been made upon the power supply during a certain specified time. To accomplish this we have the *Wright demand indicator.* The device consists of a *U*-shaped tube terminating in two bulbs,

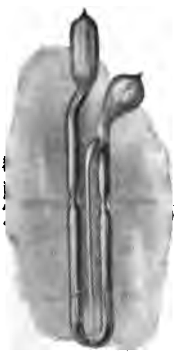

FIG. 269.—Wright-Demand indicator tube.

FIG. 270.—Wright-Demand indicator with shunt.

a branch tube connecting to one of the legs as shown in Figs. 269 and 270. A current-bearing coil surrounds one of these bulbs, the heat of the energy loss increases the gas pressure in the tube and forces the liquid upward in the other tube. An amount of liquid overflows into the indicator tube, the quantity depending upon the value of the maximum current and the length of time it lasts. The lag due to the time taken to heat the air is such that rapid fluctuations are not taken into account unless they occur

frequently enough to increase the air temperature. A current value lasting

4 minutes records 90 per cent. of its value.
10 minutes records 97 per cent. of its value.
40 minutes records 100 per cent. of its value.

By this characteristic, starting currents, short-circuits, etc., are not effective in establishing the basis of payment for energy. The indicator may be calibrated in amperes, in which case the reading indicates that part of maximum current which has existed for one of the specified periods during the whole time since the meter was last adjusted by emptying the overflow back into the *U* tube. The resetting is done by simply tilting the tube.

The indicator is used upon alternating-current or direct-current circuits interchangeably up to the sizes where shunts or transformers become necessary. When such additions are required owing to the high alternating-current voltage or to large values of current, the two types become independent.

Rates.—There are four fundamentally different methods of determining the rates of payment for electrical energy, namely:

1. Flat rate.
2. Meter rates.
3. Segregated rates.
4. Load factor rates.

The *flat rate* is a fixed charge for service, regardless of the number of hours per day load is taken, or its exact amount. It may be illustrated by the charge made to a city of (say) $85.00 per lamp per year for street arc lighting.

Meter rates may be of various kinds. One simple method is a *uniform rate* for all energy consumption as indicated by the meter reading. Another scheme which presents better features is the *two-rate meter*, where a special device is required to record what part of the consumption occurred at "peak" hours and what part occurred at "valley" hours of the total load. Charge is then made at the higher rate for the energy used when the plant was carrying its heavy peak load. If it is practicable for an industry to use its maximum power during the "valley" hours of

the power company's load, it can do so to the mutual advantage of itself and the power company.

Segregation of charges is accomplished by separation of expenses for power production and distribution. The *Hopkinson system* makes one charge based upon the *load capacity* of the consumer's circuit and a second charge upon *registered consumption.* The idea is that each customer should pay for the privilege of service in proportion to that amount which he may at any time secure, while the method of computing the whole charge should allow of reduction if no such consumption takes place.

The *Doherty system* divides the charge into three parts, for *service, demand,* and *energy.* A fixed sum is charged, for establishing and maintaining service connections; the maximum demand is the basis for the second charge and is generally based upon the number of lamps, etc., installed; the third part of the charge is based upon actual consumption.

Still more analytical methods of charging are possible, however, by studying the load factor of individual consumers and the load factor of the system. In this scheme, the general attempt is made to carry much further the two-meter method, accomplishing the result by various devices. The demand indicator, previously described, records the maximum demand made upon the system, and charge may be made accordingly. This contemplates only the load factor of the consumer's circuit, and is, hence, faulty in principle because the relation between the consumer's load variations and the load variations of the system is of prime importance. For example, a distributor can ill afford to add to his regular load a circuit with poor load factor if the peak epoch thereof coincides with the peak epoch of his already overloaded system. He can, however, very well afford to take this additional load if the peak helps to fill his valley. It is, therefore, of considerable importance to him to know, not only the amount of the maximum demand, but also the customer's whole load characteristic including the time at which certain loads occur. For this reason, instruments are installed in some systems which record at suitable intervals the power supplied to the consumer.

It is the case, however, that, when the load upon the whole system is nearest to the capacity of the system, cost of operation

is a minimum. When running under minimum load cost of production is a maximum. Hence, any difference of charge contemplating a low rate in the "valley" region of the system will give the anomalous condition of a smaller price for the more expensive product. This practice is, nevertheless, defensible upon the ground that extra inducement is offered to fill up the valley and to lower the peak, thus lowering the average cost of production. That is, the effect upon price of production is beneficial when a load is added whose load factor is the opposite to that of the system. What is of prime importance is, not that the load factor of the minor circuit is poor, but, that its effect upon the load factor of the system is beneficial.

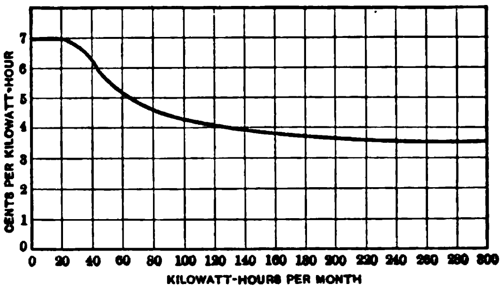

FIG. 271.—Contract rate curve for power.

Added to all of the foregoing primary systems of charge discounts may be introduced. One method is to determine the amount of discount with reference to the load factor of the customer, *i.e.*, the ratio of average load to connected load. Again discounts may be allowed for excess energy consumption above a specified amount. Another way of accomplishing this same result is to give a curve of rates plotting the price in cents per kilowatt-hour against kilowatt-hour consumption for the month. This becomes practicable for a motor installation where it is impracticable for a lighting load. Such a curve is shown in Fig. 271. For large users of power the rates may take the tabular form given in Table XXXVIII.

Again the charge may be complicated by a combination of several of the above features and by an additional cash discount.

A Doherty rate thus supplemented may read thus:

First charge....................	$ 9.00 per customer.
Second charge..................	24.00 per horse-power per year.
Third charge	0.03 per kilowatt hour.
Discount for cash..............	10 per cent.

Table XXXVIII.—Contract Rates for Electrical Energy.

Range within which falls the consumption in kilowatt hours.	Price in cents per kilowatt hour up to lower limit of kilowatt-hour range.	Price in cents per kilowatt hour for excess over lower limit of kilowatt-hour range.
0– 100	6.0	6.0
100– 200	5.0	5.0
200– 300	4.0	4.0
300– 500	3.0	3.0
500– 1000	2.5	2.5
1000– 2000	2.5	2.0
2000– 3000	2.0	1.6
3000– 5000	1.6	1.35
5000– 10000	1.35	1.1
10000– 20000	1.1	1.0
20000– 40000	1.0	0.93
40000– 80000	0.93	0.88
80000–150000	0.88	0.85
150000–	0.84	

CHAPTER XIII.

LINE PHENOMENA.

Inductance and Capacity.—From the formulæ derived in an earlier chapter we may calculate the values of L and C for a mile of any given transmission line if we have the distances between wires and wire diameters. It may, however, be the case that early in the stage of development these distances are not known, yet approximate values of inductance and capacity are desired in order to estimate the reactance. If the values of L and C are calculated for rather widely varying sets of conditions, we get such values as are shown in Table XXXIX, where the interaxial distances are taken as 48 and 144 inches and the diameters of wires are 0.325, 0.500 and 1.000 inch. It will be seen that

TABLE XXXIX.

	48 inches.		144 inches.	
2r	L, mh.	C, mf.	L, mh.	C, mf.
0.325	1.83	0.0156	2.18	0.0133
0.500	1.69	0.0169	2.04	0.0140
1.000	1.47	0.0195	1.82	0.0157

the range covered by L, with a change in interaxial distance from 48 to 144 inches and from the largest wire given to the smallest one, is only from 1.47 millihenrys per mile to 2.18 millihenrys per mile. Generally, it would be safe as an approximation to use an average value of about 1.80 millihenrys per mile. Similarly, for C an approximate value of 0.0160 microfarads per mile may be used without serious error.

Where L is known (perhaps by measurement) C may be calculated although the spacings, etc., are not given, if length of line is known. This would be done by use of the two fundamental

formulæ for natural frequency for the line and for resonance condition.

$$\frac{47000}{l}=f_0, \text{ natural frequency.}$$

$$2\pi f_0 L=\frac{1}{2\pi f_0 C}, \text{ resonance condition.}$$

Whence

$$\frac{47000}{l}=\frac{1}{2\pi\sqrt{LC}}$$

or

$$C=\frac{l^2}{2\pi(47000)^2 L}=13.6(10^{-9})\frac{l^2}{L} \text{ farads.}$$

$$=13.9\frac{l^2}{L} \text{ microfarads.}$$

Oscillations and Surges.—When a line containing series inductance, capacity and resistance is allowed to reach stable running conditions, it is readily seen that at the instant when current is a maximum, the magnetic interlinkage is a maximum, and the charging current is maximum. This means that the storage of inductive energy is a maximum but condensers are not charged and capacity energy is zero. When the cycle has progressed to the point where condensers are fully charged, current becomes zero and the magnetically stored energy is zero. That is, when capacity storage is greatest, inductive storage is the least and contrawise. We have, in such a system, therefore, the possibilities of an oscillation of stored energy from one condition to the other, if it is once started.

The energy stored inductively is measured by the expression $i^2L/2$; the energy stored in capacity is $e^2C/2$. In order to make possible the surging back and forth of any considerable quantity of energy both of these expressions must be large. Large capacities are not common but high voltages are common and taken in conjunction with moderate capacities, may give considerable energy storage. Large currents and high inductances are both common. The long-distance transmission line presents one group of conditions which subjects it to the likelihood of this

trouble. The underground cable system, having lower voltage but higher capacity, also furnishes a field for such disturbances.

If the oscillatory exchange is of rapid action, it is generally spoken of as an *oscillation*. With low frequency, especially, of heavy-power exchange, the term *surge* is used. The frequency of the oscillation is determined by the constants of that portion of the total circuit which is affected. It is the natural frequency of this circuit and is shown by

$$f=\frac{1}{2\pi\sqrt{LC}},$$

provided inductance and capacity are concentrated and not distributed. Resistance in the circuit is the toll gatherer, inasmuch as the transfer of energy from one form to the other involves the flow of current and introduces i^2r losses. So also are losses effected by the core loss in any iron-cored member of the circuit. The ratio of these losses to the total energy surging back and forth determines the length of time the surge will last. In fact, the dampening effect of resistance may be so great that the surge or oscillation is impossible and only a dying out is permitted. This gradual discharge would then be accomplished along a logarithmic curve. The critical point is when

$$r^2 = 4xx_c,$$

where
r = resistance of circuit,
x = inductive reactance of circuit,
x_c = capacity reactance of circuit.

We have, then, the conditions

$r^2 < 4xx_c$, giving oscillatory discharge,
$r^2 > 4xx_c$, giving logarithmic discharge.

Naturally the term $4xx_c$ may be replaced by its equivalent $4L/C$.

Referring again to the expression of frequency of the oscillation, it is readily recognized that, in order to have a low-frequency surge, the values of inductance and capacity must be high. This condition would likewise introduce the dangerous state of affairs of large reservoirs of energy. A low-frequency surge is correspondingly destructive. The conditions are not easily obtainable except in connection with transformer-fed cable systems, because the ordinary aerial line has much less capacity

than has the cable line. Nevertheless, with the high voltages of to-day, oscillations of energy may occur at higher frequencies with quite destructive effects.

Nothing has yet been said of how these oscillations or logarithmic discharges are to originate. To state this briefly is to say that any change of circuit conditions leaves these quantities of stored energy in an unbalanced relation to each other. The adjustment of these relations gives the phenomena we are speaking of and its duration is generally limited. In by far the largest number of normal operations the transient phenomena accompanying some regular or accidental step in the process are negligible or of minor importance. But frequently their presence may need to be recognized and taken into account in design of apparatus or manipulation of circuits. Again, there are conditions where the transient term is large and periodic, with a period shorter than the time required for its disappearance and, hence, it becomes of paramount importance. This last case is well illustrated in the field current of a generator controlled by a "Tirrill" regulator. Probably the most serious disturbance upon a line will occur when a short-circuit is interrupted.

As an instance of what may occur under abnormal conditions to set up disturbances, the case of an unstable ground connection upon a line of considerable capacity and inductance is a clear illustration. The point in question is at a high potential above ground until the breakdown of insulation occurs. The potential between the two is immediately reduced from this high value to zero. The electrostatic distribution is changed, as is also the electromagnetic effect. But as soon as voltage to ground falls below a certain point the poor connection may break the arc. Immediately the potential of the line rises and the conditions attempt to become normal. The rise in voltage causes a new breakdown and the disturbance continues.

This trouble can almost ruin a cable system, which may be considered peculiarly liable to it.

Switching.—There are at least four cases of switching under ordinary circumstances which are of prime interest from the standpoint of operative trouble. These are

1. Charging a main line by high potential.
2. Opening the above line.

3. Charging a branch line.
4. Opening branch line.

In the first place, when lines are charged the maximum potential reached cannot exceed twice that normally read at the given point upon the line. The transient term cannot more than double the voltage. This will be true of either the main line or the branch line. If, therefore, a main line of considerable magnitude is tapped near its extremity by a short branch, the voltage in the main line may approximate double potential and thus supply an excessive voltage to the small branch line. This, again, may tend to increase above its supply and a greater excess of voltage may be reached upon the branch if thus excited during the existence of the transient term in the wave of the main line. Ordinarily, such rises are much limited by losses, etc., and never reach double values. The cases 1 and 3 need not be considered as presenting serious liability to trouble.

Opening a line may be just as simple an operation as closing it, or it may give rise to trouble. This depends upon the current ruptured and the point upon current curve where the break occurs. An oil circuit breaker opens the line at the zero point on the wave and causes no disturbance. If the line is opened by an arcing across the switch clips, as in open air, there is great danger of setting up a cumulative oscillation which will destroy insulation or apparatus. Switching troubles are most apt to occur in that portion of a circuit in which there is considerable inductive reactance and low capacity. If the energy storage is large we have:

$$\frac{i^2L}{2} = \frac{e^2C}{2} = \text{large quantity.}$$

Hence, if L is large, i is moderate and C is small, e must be large. This causes extreme potential rises. Difficulties are more apt to arise with transformers and reactive coils than with transmission lines or cable systems.

Because of these tendencies, low-voltage switching is practised wherever feasible, the circuits being closed or opened upon the low-potential side of the transformer.

Another source of danger is in handling idle lines. If a line is cut off from generator and load by opening at the point of zero

current, the whole of the energy stored therein is present in the electrostatic charge of the line to high potential against ground. The line is idle but not dead and it will discharge to ground through the body of anyone touching it. It is, therefore, *always* preferable to ground idle lines before handling them.

Wave Length.—As the electrical impulse travels 188,000 miles per second (in air or along aerial lines, though not in cables or machines), the statement that a certain circuit receives current at 60 cycles per second determines for us the wave length or the space covered by one wave. It will be $188{,}000 \div 60 = 3133$ miles from crest to crest. Hence a line 3133 miles long will be receiving a 60-cycle current at one end and supplying it to the load at the other end one cycle behind time. The generator end of a line one-quarter as long, 784 miles, will be at zero potential in its wave when the receiver is at maximum potential. For a 25-cycle circuit, the wave is 7520 miles in length and the quarter wave is 1880 miles long.

When we deal with the more rapid changes such as occur in the current in a telephone circuit, the wave length becomes much shorter. These waves are very complex and the higher harmonics are very important to the clear vocalization. Considering, then, one of the harmonics of a frequency about 3000 cycles per second, we find that its wave length is only about 62.6 miles. That is, a telephone line 65 miles long would "contain" a complete wave of this harmonic at any given instant.

In a transmission line of quarter wave length, Steinmetz has shown that with a constant potential supply, the circuit tends to regulate for a constant current load and vice versa. This means that with constant potential supply, the rise in terminal voltage at the receiver end of the line will be great for open circuit. The tendency in this direction is present in even shorter lines if they are long enough to approximate the quarter wave condition, and, hence, long transmission lines are liable to give poor regulation characteristics and poor operation conditions for synchronous apparatus.

Waves.—The building up of voltage due to certain relations between wave length and line length may be likened to the addition of reflected waves to the primary waves. In fact, the mathematical expressions for the conditions existing in a circuit

occur in the exact form for a wave and its reflection from the end of the circuit. If, then, the interrelation of lengths is at the critical point, the rise is theoretically infinite. This critical point is the quarter wave length for the line.

To carry the illustration farther, if a line branches into numerous circuits, each one will have a reflection condition of its own and the main line will add all of these reflected components. At each branching point or change in line characteristics a partial reflection occurs, as does also a partial transmission. The transmitted component is not necessarily in exact phase with the received wave because the reflected component has been subtracted. The analogy of reflection, therefore, necessitates as a corollary the concept of refraction.

The phenomena occurring in a *fixed circuit*, however varied its local characteristics and however much it branches, must be distinguished from those occurring due to *changes in circuit conditions*. We have already pointed out that in the case of the latter, the frequency is determined by the quantities L and C and the duration of the disturbance depends upon r. In fixed circuits, however, the impressed voltage is the variable and the phenomena depend upon its change, that is, upon its frequency, wave-shape, etc. Certain conditions of circuits give peculiar resultant waves for the combined main wave and reflected wave. Taking, for convenience, the sine wave only into account, we will consider two of the cases, *standing waves* and *traveling waves*.

The combination of the main wave with the reflected wave will give zero points or nodes along the line. When these nodes remain stationary, waves likewise remain in a fixed position, although varying in value, and we have the *standing wave*. When the resultant zero point does not have a fixed position upon the line, the resultant wave is a *traveling wave*. It and the node travel but not at the full velocity of the main wave. The direction of travel is away from the source of power supply.

The *standing wave* may be represented by a sine wave upon the zero axis and will be of such frequency and wave length that the transmission line must be a multiple (odd or even) of the quarter wave length. That is, the line is one-quarter, one-half, two times, . . . the wave length, depending upon circuit conditions. This standing wave dies out in one or the other of

two ways, (1) decreasing according to simple or combined exponential laws or (2) oscillating through zero values to maxima and minima that decrease according to these simple or combined exponential laws. That is, the time component of the mathematical expression for the standing wave may contain

(1) Simple or compound negative exponentials in time, or

(2) A product of negative exponentials and trigonometrical functions in time.

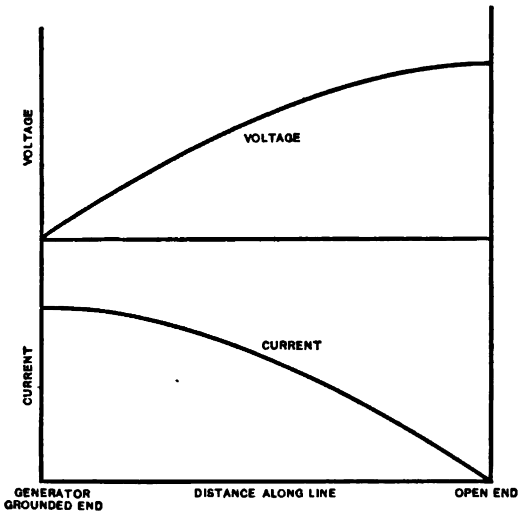

Fig. 272.—Energy storage on line, quarter wave length.

The "attenuation" or "decrement" factor of a standing wave is generally* greater than zero because the wave is an oscillation of stored energy from one form to the other, and in so exchanging conditions the energy storage occurs with different distribution over the quarter wave length unit of line. This passage of energy over the line is accompanied by energy loss, so that the wave gradually dies out. To illustrate this, take a line of quarter wave length open at the end distant from the generator. Suppose the generator is suddenly cut off from line and line is grounded around it. The electrostatic storage of energy may

* There are possible certain conditions of circuits where the oscillation is cumulative and continues to build up till destruction occurs or till further increase is interfered with, as by some means which may increase the losses.

be shown by one of the numerous possible positions of the voltage wave as in Fig. 272. It is maximum at the open end of the line and minimum at the grounded end. But now the electrostatic energy is converted into electromagnetic energy by a discharge of this potential by means of current in the line. This current will reach a maximum at the grounded end of the line, and consequently, so will the electromagnetic energy. That is, the current of the line and the electromagnetic energy distribution are shown by a second curve in Fig. 272. These two conditions, maximum voltage and maximum current, do not occur simultaneously but at a time interval corresponding to a quarter cycle.

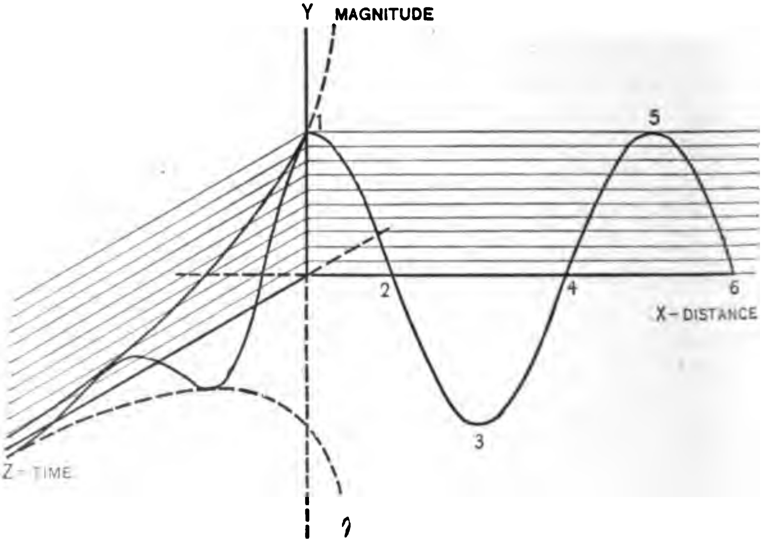

FIG. 273.—Three co-ordinate representation of standing wave.

It is seen that the energy stored is differently distributed over the quarter wave length line for the two conditions of storage, as originally stated. Hence, the transfer from one condition to the other will dissipate energy and eventually cause the standing wave to disappear.

Perhaps a clearer idea of the standing wave may be acquired by using the three coordinates, x, y and z of solid geometry for *distance*, *magnitude* and *time*, respectively, as shown in Fig. 273.

We may assume the case of a line open-circuited at the generator end (by circuit breaker) and short-circuited at the other end (by grounding). Then the voltage will be great at generator end and current zero, while current will be great at the distant end and voltage zero. The voltage curve, therefore, is shown by the cosine wave upon the x-axis, being maximum at distance equal to zero, etc., thus

e is max. when $d=0,\ l_o;\ 2l_o,\ \ldots$
e is min. when $d=0.5l_o,\ 1.5l_o,\ 2.5l_o,\ \ldots$
e is zero, when $d=0.25l_o,\ 0.75l_o,\ 1.25l_o,\ \ldots$

Time varies in the positive direction of axis z.

First Case.—Every value of voltage shown upon the cosine wave discussed decreases logarithmically as shown by the yz curve indicating exactly how the voltage 1 at open end changes. Voltage 3 changes similarly from its minimum value to zero at infinite time. Voltage 5 is exactly similar to voltage 1. Voltages 2, 4 and 6 start at zero and remain there. The topographic map upon the time-distance plane shows parallel hollows and ridges of depths and heights, respectively, decreasing with passing time.

Second Case.—The same xy curve obtains at zero time, but with passage of time the voltage 1 *oscillates* between successively decreasing maxima and minima whose crests follow the exponential curves. Voltage 5 has an identical sequence; voltage 3 has the corresponding negative sequence; voltages 2, 4 and 6 continue at zero. Intermediate voltages oscillate between lesser maxima and minima following the same law of decrement. The topographic map upon the time-distance plane shows a checkerboard of mountain peaks and basins decreasing in height and depth in the direction of increasing time.

In either case, a section of the surface by a plane parallel to the xy-plane will give a true cosine wave. That is, the space distribution is always trigonometric. Any curve shown by a section parallel to the yz plane is exponential in the first case, or an exponential-trigonometric product, in the second case. In standing waves, there is no energy transmission along the line through nodal points.

In *traveling waves*, there is transmission of energy along the line. The travel must be away from the end of the line from

which energy was originally supplied, because the reflected wave is always smaller than the main wave due to losses.

The simplest case of the traveling wave is that for a line of infinite length and, consequently, having no reflected components. Here it becomes the simple sine wave moving at speed of full frequency. With an open line of limited length, however, the reflected wave will be present and the peculiar result will be noted of nodal points with unequal spacings, due to the fact that the successive cycles of the reflected wave are not of constant magnitude and hence combine differently with the main wave.

Corona.*—It has been found that as parallel conductors are subjected to higher and higher voltages, there comes a time when the potential reaches such a value that considerable energy discharge or leakage occurs between the two conductors. When once this value of voltage is attained, the *critical voltage*, a continued increase in potential is accompanied by a very rapid rise in energy loss. As the discharge becomes appreciable, the conductors are surrounded by a luminous envelope having a bluish tinge. The diameter of the envelope increases as the voltage is further increased. This phenomena is known as the *corona effect.*

It is quite likely that the air surrounding the wire becomes conducting and increases the effective diameter of the conductor. This is a direct result of reaching high values of potential that the strain set up in the space surrounding the conductor is greater than the medium will withstand. It is the same phenomenon which takes place preceding rupture between needle points of a spark gap and, in fact, it presages rupture from line to line.

As is well known, however, the potential gradient at the surface of a conductor depends upon, not only the voltage of the line and its distance from the return line but also the curvature of the surface of the conductor itself.

It is undoubtedly the case that the breakdown of air as an insulator progresses rather slowly at first due to the fact that it requires a definite amount of energy to accomplish it. The expenditure of this energy in the vicinity of the conductor

* A rigorous discussion of the conditions accompanying and affecting the corona is not attempted here. For such data, the reader is referred to various papers presented before the A. I. E. E. Especially, attention is directed to papers by Ryan (1904, 1911), Whitehead (1910) and Peek (1911).

surface causes chemical changes in the air and also produces heat and light.

As previously derived, in the discussion of the capacity of a transmission line, the potential of a particle which moves from the center plane between two parallel conductors (see Fig. 194, Chapter VIII) to the surface of one of the conductors, will be expressed by

$$E=\int_r^{\frac{d}{2}}\left(\frac{2Q}{x}+\frac{2Q}{d-x}\right)dx=2Q\log_e\frac{d-r}{r}.$$

This potential is, then, the potential of the conductor, or the difference between its potential and that of the neutral plane, which is taken as zero.

At any intermediate point, as x_1, the potential will be

$$E_{x1}=\int_{x_1}^{\frac{d}{2}}\left(\frac{2Q}{x}+\frac{2Q}{d-x}\right)dx=2Q\log_e\frac{d-x_1}{x_1}.$$

The potential gradient, as x_1 varies, is

$$\frac{dE_{x1}}{dx_1}=-2Q\frac{d}{x(d-x)},$$

But

$$2Q=\frac{E}{\log_e\frac{d-r}{r}}.$$

$$\therefore\quad\frac{dE_{x1}}{dx_1}=-E\frac{d}{x_1(d-x_1)}\cdot\frac{1}{\log_e\frac{d-r}{r}}.$$

If, then, the value of the potential gradient exceeds the potential which air will stand, there will be at least partial rupture and energy discharge. As the value of x_1 is limited and can be not less than r, and not greater than $d-r$, the potential gradient cannot become infinite, but will be a maximum at these two extreme values of x_1, that is, at the surface of the conductor. With this condition, d is large compared to x and we may write

$$\frac{dEx_1}{dx_1}=\frac{E}{x_1}\cdot\frac{1}{\log_e\frac{d-r}{r}}.$$

Or, as $x_1 = r$ and d is much greater than r,

$$\frac{dE_{x1}}{dx_1} = \frac{E}{r \log_e \frac{d}{r}}.$$

This is the fundamental equation for the corona. However, the application of the equation is not very simple, because the numerical value of voltage to which this expression must be placed equal is not easily obtained with any great degree of accuracy. For ordinary conditions of atmosphere at or near sea level without such impurities as salt, etc., it is probably safe to use for air 70,000 volts per inch. That is,

$$70{,}000 = \frac{E}{r \log_e \frac{d}{r}}$$

where

E = voltage to neutral to start corona.
r = radius of conductor in inches.
d = distance between centers of conductors in inches.

Calculated from this equation, the critical voltages which may not be exceeded without corona losses are tabulated for certain combinations of radii of conductor and conductor spacings in Table XL.

Table XL.—Corona Voltages.

Gage number.	d = / r	48 in.	60 in.	72 in.	96 in.	120 in.	144 in.
4	0.1022	38500	39900	41300	42700	44100	45500
3	0.1147	42700	44100	45500	47600	49000	50400
2	0.1288	46900	49000	50400	52500	54600	56000
1	0.1446	51800	53900	55300	58100	60200	62300
0	0.1624	56700	59500	60900	63700	65800	67900
00	0.1824	62300	65100	67200	70700	72800	74900
000	0.2048	68600	72100	74200	77700	80500	82600
0000	0.2300	75600	79100	81200	85400	88900	91700
	0.2500	81200	84700	87500	91700	95200	98000
	0.5000	147000	147700	153300	162400	168700	174300
	1.0000	238700	252000	263200	281400	295400	306600

For lower atmospheric pressure, as that at high altitudes, the value of the voltage air will stand without rupture must be decreased very materially. This may account for the large differences between values given by different authorities. It will even depend upon meteorological conditions from day to day. Wave shape will have its effect upon the critical point, as the discharge is evidently dependent upon the maximum value of voltage rather than the effective value provided the peak is not too sharp. The flat topped wave, therefore, will give less discharge than a pointed wave of the same effective reading.

Corona will occur with any medium between the conductors, oil, rubber, paper, etc. The material used, however, possessing, as it does, a different dielectric strength, will not give the same critical point as will air.

From the foregoing, it is evident that, for the same conductivity, aluminium conductors will give a lesser corona discharge than will copper at any given potential, because the wire has a greater diameter. With increase of line voltages now contemplated, it is very probable that aluminium will be adopted frequently because of this one advantage. The use of insulated or covered conductors is, as yet, important only in underground work, but it may affect aerial lines at some future time, as rubber has, probably, three times the dielectric strength of air and oil has about twice the value.

Special applications of compressed air may be made in connection with insulating bushings, oil switches, etc., as increased pressure will raise the critical voltage point.

When a transmission line is running at or near the critical voltage, a slight rise in potential will rapidly increase the discharge to atmosphere. Hence, it has been asserted that a lighting disturbance to a line in such a condition of operation will not be serious. The increased charge cannot be taken by the line which, therefore, cannot transmit the disturbance to the power-house or substation. In other words, it is expected that a line running near the critical voltage point will be self-protected and will need no lightning arresters. Such conditions are being tried upon the line of the Grand Rapids and Muskegon Power Company, and, so far, no serious trouble has resulted from the practice.

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